WTEC Panel on

MICROSYSTEMS RESEARCH IN JAPAN

FINAL REPORT

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ABSTRACT

This report reviews Japan's research and development activities and strategies in the field of microsystems and microelectromechanical systems (MEMS). Topics covered include the future outlook of national initiatives, interactions between industry and universities, technology and manufacturing infrastructure, and emerging applications research. The panel's findings include the following: non-silicon microsystem technologies, together with parallel assembly technologies for low-cost mass manufacturing, merit increased attention. Incorporating non-silicon technologies into the MEMS Exchange should be considered, in order to identify, support, and standardize U.S. capabilities. Opportunities should be identified for exploiting early applications of synthetic nanostructures in microsystems. Metrology, process control, and device standardization should be pursued, in collaboration with Asia and Europe. Additional findings are outlined in the panel's executive summary.

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EXECUTIVE SUMMARY

In order to assess Japan's research and development activities and strategies in the field of microsystems, the NSF, DARPA, NIST, and ONR funded a study mission to Japan, under the auspices of the World Technology Evaluation Center (WTEC). The timing of this study coincides with the end of the ten-year Micromachine Technology Project (MTP) in 2001, which has prompted discussions on future funding for research in this general area. The committee visited eight university research groups, seven corporate laboratories, one national laboratory, and the Micromachine Center, which managed the MTP. In addition to the major goal of understanding the long-term strategies for research on technology and applications in microsystems, the committee was charged by the sponsors to observe mechanisms for university-industry interactions, to gather information on bio-MEMS and RF MEMS activities in industry, to report on efforts to formulate standards, and to discuss educational initiatives inside the academic community and outreach activities to pre-college students.

The body of this report describes in detail the findings of the study and reports on each of the sites visited by committee members. The Japanese research community is currently evaluating the lessons learned from the MTP. In particular, we found that Japan is adapting the U.S. model of targeted research funding for applications with relatively near-term prospects for commercialization.

Early in 2002, the Ministry of Economy, Trade, and Industry (METI) started a major five-year project in the area of microfluidic systems, which has great promise for biomedical applications as well as for enabling micro chemical reactors. Microfluidics has been a major research field for the past five years, with significant academic research efforts in the United States, Europe, and Asia. There are outstanding academic research groups in Japan, in particular at the University of Tokyo/KAST, Waseda University, and Tohoku University. In addition, Hitachi has incorporated microfluidic subsystems into commercial water quality instrumentation. The METI project on microfluidics therefore will build upon established technologies, in contrast to MTP's emphasis on research on basic technologies to enable visionary micromachine applications.

During the past few years, Tohoku University and the University of Tokyo's Institute of Industrial Science have built excellent microfabrication laboratories that will enhance the research productivity of these leading academic groups and their collaborators. Silicon micromachining laboratories built using MTP funding are now being advertised as foundries, which should increase access to fabrication services for Japanese industry and universities. However, the lack of an impartial, independent broker such as the MEMS Exchange in the United States means that fully utilizing the capabilities of multiple foundries is not possible. As in the United States, increased funding has led to research in synthesis-based nanotechnology by several microsystems groups. Faculty have developed graduate microsystems courses in electrical and mechanical engineering departments; however, no university has an integrated program or major in the field. The Micromachine Center has established a picture contest for elementary school students that has increased awareness of microsystems among Japanese youth.

Technology transfer from university research labs to large companies is facilitated by industrial visitors, a system that appears to work well. Technology licensing offices have recently been created at the major universities, and intellectual property regulations have been amended to promote licensing of university patents by industry. Institutions are still adapting to these changes. Start-up companies are not a significant avenue for technology transfer, in marked contrast to the U.S. model. Finally, the Micromachine Center has begun to coordinate with U.S. and European organizations in the creation of standards for microsystems.

Microsystems research in Japan has strong roots in mechanical engineering and in robotics, in contrast to the U.S. origination in silicon planar technology. During the 1990s, the MTP funded research in a variety of non-silicon microfabrication technologies that have yet to bear fruit in commercial applications. Emerging microsystems applications, like microfluidic systems, will require more than planar lithography-based fabrication processes. The committee was impressed by the technical capabilities of small Japanese manufacturers that demonstrated precision injection-molded microfluidic connectors and vacuum filled 3-D interconnects in a multi-chip module. These manufacturers are a ready source of precision "piece parts" for microsystems. A National Institute of Advanced Industrial Science and Technology program is making an effort to connect them to microsystems projects. Such manufacturing capabilities represent a significant competitive advantage for Japanese industry and universities, as microsystems applications are moving beyond the confines of silicon chips.

The relative assessment of Japanese microsystems technology and applications in the table below (Table ES.1) contains a current "snapshot," as well as projections for the next several years.

Table ES.1
Assessment of Japanese Microsystems Technology and Applications

Technical Area	Current Strength (Japan vs. U.S.)*	Rate of Improvement (Japan vs. U.S.)**
Micromachining Technologies		
Surface	–	=
Bulk silicon (wet)	=	=
Bulk silicon (dry)	–	–
LIGA	+	+
Micro piece parts	+	+
Integration Technologies		
Co-fabrication of MEMS and electronics	–	–
Assembly technologies (serial)	+	+
Assembly technologies (parallel)	–	–
Packaging	=	=
Applications		
Pressure sensors	–	–
Inertial sensors	–	–
Optical MEMS	–	–
Microfluidics and bio-MEMS	–	+
Data Storage	=	+
RF MEMS	–	–
Infrastructure		
University microfabrication facilities	=	=
Foundries, OEMs	–	+
Distributed foundries	–	–
Technology transfer from universities	–	+
Standards	–	=
Government Research Programs		
Application-focused programs	–	+
University project funding	–	=
Microsystems/MEMS education		
University curricula	=	=
Short courses for industry	=	=
K-12 Outreach	+	+

* A plus means Japan is leading the U.S., a minus means Japan is behind the U.S., an equal sign means Japan and the U.S. are equal in this area.

** A plus means Japan's rate of improvement is greater than the U.S., a minus means Japan's rate of improvement is less than the U.S., an equal sign means Japan and the U.S. are improving at the same rate.

The implications for the U.S. microsystems research community of this study are as follows:

- Non-silicon microsystem technologies, together with parallel assembly technologies for low-cost mass manufacturing, merit increased attention.
- Incorporating non-silicon technologies into the MEMS Exchange should be considered, in order to identify, support, and standardize U.S. capabilities.
- Opportunities should be identified for exploiting early applications of synthetic nanostructures in microsystems.
- Metrology, process control, and device standardization should be pursued, in collaboration with Asia and Europe.
- Support for outreach activities by microsystems researchers to K-12 students should be strengthened.

CHAPTER 1

INTRODUCTION

Roger T. Howe

BACKGROUND

The field of microelectromechanical systems (MEMS) has developed rapidly since its beginnings in the 1980s, with a worldwide industry becoming well established by the year 2000. From its beginnings, Japanese academic and industrial researchers have contributed substantially to the field. In the early 1990s, the Japanese government launched an ambitious ten-year program called the Micromachine Technology Project, which validated the great promise of the field and had worldwide impact. As this project began, the U.S. government was interested in understanding the state of the art and the long-term strategy for MEMS research in Japan and sponsored the 1993-94 JTEC Study of MEMS in Japan, led by Prof. Kensall D. Wise of the University of Michigan. The insights from the study's report played an important role in formulating research strategies for the NSF and DARPA during the last half of the 1990s.

Once the Micromachine Technology Project ended in 2001, Dr. Rajinder Khosla of the NSF Engineering Directorate recognized the importance of revisiting Japan, as it stands on the threshold of a new phase of microsystems research. Co-sponsored by the DARPA MEMS and MicroFLUMES programs, as well as NIST and ONR, a new study mission to Japan was organized under the auspices of WTEC in the summer of 2001. The sponsors sought to understand, in a broad sense, long-term research strategies for microsystems technologies and applications, with a specific interest in the interface between the microsystems and nanotechnology fields. In addition, the NSF was interested in Japanese activities in microsystems education and in encouraging interest in science and technology among pre-college students.

During the 1990s, the Micromachine Technology Project established a fabrication infrastructure for MEMS at several companies and funded research for ambitious applications in catheter-based surgery, in micro factories, and in milli-scale robots for machine maintenance. In addition, the Micromachine Center in Tokyo, which was funded by the project, made MEMS widely known throughout Japanese society. Major investments in selected academic laboratories were made in the second half of the decade, after the Science and Technology Basic Law was enacted in 1995. Furthermore, ground rules for handling intellectual property in Japanese universities changed, with the result that Technology Licensing Offices now exist at a variety of Japanese universities. Finally, the U.S. initiatives in nanotechnology have led to increased funding in Japan and to considerable discussion among leading microsystems researchers.

In order to fulfill its goals, the committee considered carefully the list of sites that would be visited during the one week in Japan, November 11-16, 2001. The committee divided into two teams for most of the week, in order to increase the number and geographical spread of sites that could be visited. In the end, the final list in Figure 1.1 reflects a balance among many constraints. The committee spent an entire day at Tohoku University, which is both an outstanding center for research in microsystems and yet remote from Tokyo. At each site, the host researchers presented material about their activities and engaged in discussions with committee members on a wide variety of topics. These discussions were invaluable for developing a broad perspective on the state of microsystems research in Japan. Site reports from the visit are collected in Appendix B.

University Laboratories

Osaka University
Prof. M. Okuyama
Prof. S. Takeda
Ritsumeikan University
Profs. S. Sugiyama and O. Tabata
Tohoku University
Prof. M. Esashi
Tokyo University/IIS
Prof. H. Fujita
Tokyo University/KAST
Prof. T. Kitamori
Tokyo University/Hongo Campus
Prof. S. Ando
Waseda University
Prof. S. Shoji

Industrial Laboratories

Hitachi Ltd.
Mechanical Engineering Res. Lab.
Murata Manufacturing Co.
Yokohama Technical Center
Olympus Optical Co., Ltd.
Corporate R&D Center
Omron Electronic Components Co.
Kyoto
Sony Corporation
Corporate Technology Dept.
Toyota Central R&D Laboratories
Electronic Device Division
Wacoh Corp.

National Institutes

Advanced Industrial Science and Technology
ISEMI Laboratory
Micromachine Center

Figure 1.1. List of sites visited during November 11-16, 2001.

OVERVIEW OF THE REPORT

The committee met on November 17, 2001 to discuss our impressions from the week of meetings with Japanese researchers and ways to best present them. A workshop was held on January 17, 2002 in Arlington, Virginia, in which the results of the study were outlined. The division of this report follows that of the workshop.

In Chapter 2, Khalil Najafi assesses Japanese funding initiatives in MEMS, including the impact of the recently completed Micromachine Technology Project (MTP). He describes the different experiences of Japan and the United States with MEMS research and commercialization during the 1990s and how these have affected post-MTP research strategy. A number of lessons have been learned from the MTP, such as the need to have a well defined applications focus and to provide for infrastructure development. The new five-year METI program in microfluidics represents a shift in research funding strategy toward the U.S. model of targeted DARPA microsystems programs. The 1995 Science and Technology Basic Law has improved the funding of several of the leading academic research programs in microsystems, as well as changed the legal framework for intellectual property in public universities. The U.S. National Nanotechnology Initiative has stimulated the Japanese government to increase funding in this area. As in the United States, there are several leading microsystems researchers involved in nanostructure research and in shaping government projects in this area. Additional initiatives that may start in 2002-2003 include a Ministry of Agriculture program in cell-based biochemistry and a program in micro power generation. These initiatives, taken together, will provide very effective funding of high-payoff application-oriented research.

In Chapter 3, Elliot Hui discusses several aspects of university and industry interactions in Japan, including the industrial funding of university research, technology transfer, and the role of the newly established Technology Licensing Offices (TLOs) in commercializing academic research. With respect to education in microsystems, Ritsumeikan had the most extensive curriculum, with four graduate courses in systems, devices, processes, and materials. Waseda had a multi-project chip design unit incorporated into its undergraduate course. In several universities, the graduate students and visiting researchers included several from other Asian countries and a few from Europe.

The leading academic research groups were found to have extensive ties with Japanese companies, with Tohoku University receiving half its funding from industry. At Ritsumeikan University, an industrial consortium has been formed to promote interaction between microsystems researchers and 50 companies. Japanese universities surpass their U.S. counterparts in their number of industrial visitors. These visitors often bring their own projects and use the university facilities and research environment. Tohoku University has developed a policy whereby conflicts between visitors from different companies are avoided by keeping all work in the university laboratory completely open. Tohoku has a strong track record in technology transfer, dating back to the 1970s. In all the universities we visited, the subject of intellectual property was a topic for considerable discussion. The recently formed TLOs are still being established, with the resources allocated for their support being quite limited in some cases.

Dave Monk reviews the visit's findings on foundries and infrastructure for microsystems in Chapter 4. Computer-aided design (CAD) tools for microsystems are not extensively used in Japan; rather, a "build and test" approach is used for product development. The wide variety of microstructure technologies being used for research and development makes the application of CAD tools more challenging. Microsystems foundries are needed in order to minimize development time for new products and to avoid large investments in under-utilized fabrication facilities. In response to this need, Omron in fall 2001 announced the opening of a silicon bulk-micromachining foundry at its Minakuchi plant. Several other companies have announced surface micromachining foundries, and Ritsumeikan University is starting a LIGA foundry. At the ISEMI laboratory at AIST, a national institute, there is a program to develop low-cost technologies for microsystems based on a network of manufacturers. However, there is no impartial broker equivalent to the MEMS Exchange in the United States.

The lack of standards for either fabrication and packaging technologies or for test procedures is recognized as an impediment to the commercialization of microsystems. The Micromachine Center has launched a three-year project to develop standards for thin-film testing and is collaborating with efforts by NIST in the United States and NEXUS in Europe.

Chapter 5 gives a perspective by Andrew Berlin on the role of microsystems in Japanese industry. Wacoh was one of the industrial sites visited by a part of the committee. This small company was founded in 1988 and was the first and, for a number of years, the only start-up in Japan in the microsystems field. In contrast, several hundred companies have been formed during the last five years alone in the United States. Recent changes in the intellectual property environment in Japan have led to the formation of several start-ups in the past several years. The newly established technology-transfer mechanism is not functioning smoothly yet, however.

The recent drive to open foundries is motivated by the need for under-utilized fabrication facilities to make money. However users, particularly in the case of the Omron MEMS Foundry Services, will have to overcome their reluctance to submit designs to a company that is actively involved in designing and building MEMS-based products. Japanese industry benefits greatly from its ability to send engineers to academic laboratories to be educated in state-of-the-art microsystems research. The interactions with academic groups can also lead to a better understanding of the role of microsystems in commercial products. At the University of Tokyo, Prof. Hiroyuki Fujita's perspective on commercialization strategies is similar to that of U.S. venture capitalists. Bio-MEMS is being pursued by a number of academic research groups throughout Japan. There are many opportunities for Japanese industry in microsystems, but to date high-volume, high-profit applications have yet to be found.

Mineo Yamakawa highlights emerging microsystem applications in Chapter 6 of this report. Although we visited several companies with major businesses in wireless components and devices, such as Murata, Omron, and Sony, we did not see any major interest in RF MEMS. Rather, the main focus of applications research is bio-MEMS, with the new METI project concentrating on microfluidic systems. Hitachi's Mechanical Engineering Research Laboratory has commercialized a water quality analysis system based on a microfluidic chip and has plans to increase efforts in bioanalysis applications like DNA and protein sequencing. Prof. T. Kitamori's Integrated Chemistry Project at KAST has developed innovative approaches to both analysis and synthesis using multiplexed microfluidic systems. His group has also developed a new approach to single-molecule detection called the thermal lens microscope. Of the many catheter-related projects started with MTP support, Olympus Corporation is continuing to pursue actuated catheters for both medical and industrial inspection applications. In addition, Olympus has developed a free-flow electrophoresis system for rapid sample preparation. Omron also has long-term interests in the biomedical applications of MEMS. Many university research groups have demonstrated technology that could have biomedical or chemical synthesis applications.

Mark Allen reviews the status and future directions for microsystems technologies in Japan in Chapter 7. The definition of what constitutes "MEMS" is critical to evaluating Japanese technologies. In the 1990s, the United States focused on exploiting silicon planar lithography as the core technology for microstructure fabrication, whereas Japan explored a wide variety of technologies. Some of the Japanese work, such as the micro-car fabricated at Denso, was based on extensions of traditional machining processes. In the United States, assembly of discrete components was avoided as violating the paradigm of batch fabrication, but this approach was required for the micro-catheter projects funded by the MTP. Over the past few years, the differences have blurred, as U.S. researchers have begun to explore a broader range of materials and assembly techniques and Japan has invested in monolithic planar technology.

The dominant philosophy in Japan was that micromachining technology was not an end in itself as an enabling technology. Rather, it would be used where appropriate and as needed, to accomplish a particular system requirement. At the academic and industrial sites, we found a wide range of advanced fabrication tools and processes, including LIGA and its extensions, micro-stereolithography, and e-beam lithography. The range of materials seen in Japan was broader than in the United States, with more activities in ferroelectrics, piezoelectrics, and ceramics. Although there was equipment for thin-film deposition and etching, these surface micromachining processes were not as common as in the United States. The analytical equipment in many academic laboratories was superior to that in the United States. The ability of many small, specialty manufacturers to produce micromachined piece parts is a resource for Japanese microsystems research, especially for microfluidic systems. Finally, there is little or no work on highly integrated systems based on co-fabrication of microstructures and CMOS, in contrast to the United States and Europe.

Chapter 8 summarizes the main conclusions that we draw from our research on microsystems technologies in Japan. In addition, we list some implications for U.S. research based on our findings.

CHAPTER 2

JAPANESE NATIONAL INITIATIVES, FUTURE OUTLOOK

Khalil Najafi

INTRODUCTION

The year 2001 signaled the end of Japan's Micromachine Technology Project (MTP), and the beginning of a new era in Japanese development of micro- and nano-technologies and systems. When launched in 1991, the MTP initiative influenced the landscape of MEMS and microsystems technologies not only in Japan but in the rest of the world as well. One of the most powerful industrial nations in the world had identified micromachines, MEMS, and microsystems as a critical technology for decades to come, and it had committed significant resources to ensure Japan's leadership in this emerging field. Therefore, the panel was especially interested in evaluating the contributions and accomplishments of the MTP initiative, the lessons learned, and the impact that it not only has had during its 10-year existence, but also that which it will have on future Japanese national initiatives in various fields of science and technology.

This chapter will review the contributions and impact of the MTP initiatives, will highlight a few of the notable current government initiatives in various areas of microsystems technologies, and will present a brief review of future trends and the outlook for microsystems and MEMS technologies in Japan. The chapter does not include detailed quantitative information about specific government programs, since we felt that such information is available through different channels.

THE MICROMACHINE TECHNOLOGY PROJECT (MTP) AND THE MICROMACHINE CENTER (MMC)

It is not possible to analyze the current and future research and development landscape in Japan without reviewing the Micromachine Technology Project (MTP) and its influence around the world in the last 10 years.

In 1991 the MTP was initiated by the Ministry of International Trade and Industry (MITI) with an initial proposed funding of ¥25B (approximately ¥18.5B was actually spent). It is important to distinguish between what the Japanese define as "micromachines" and what the United States and Europe define as microelectromechanical systems (MEMS) and microsystems technologies (MST). A micromachine was defined to be an extremely small machine, including milli- and nano-technologies, to accomplish a specific task. This definition is significantly broader than the MEMS definition common in the United States and even the microsystem technology (MST) definition common in Europe. MEMS researchers in the United States started their work based on integrated circuit and planar microfabrication techniques, whereas micromachine researchers came into the field from a mechatronics and mechanical engineering background. In the late 1980s and early 1990s, the Japanese economy was booming, so science and technology activities shifted to more basic and original projects, like micromachining, which was felt to be an important and critical technology for many emerging application areas in industrial plants, health care, and manufacturing.

In order to implement the goals of the MTP and to oversee their execution, MITI established the Micromachine Center (MMC) on January 24, 1992. The MMC was organized into a Board of Directors that supervised several committees: Administrative, Technical, Standardization, Cooperative Research, International, and Dissemination. The Secretariat was supervised by the Executive Director and had five departments: Administrative, Research, Information, International Exchange, and Planning. The Administrative Department provided overall coordination and support for member companies. The Research Department managed R&D grants, conducted R&D, and promoted the cooperation of multiple entities in research standardization. The Information Department coordinated the collection and distribution of information, surveyed the research on basic technology, and published a PR magazine. The International Exchange Department organized the Micromachine Summit and International Seminars. The Planning Department conducted promotion, symposium and exhibition organization, and the micromachine picture contest for elementary school children.

The MMC activities are summarized as follows:

- Generating research through the national R&D project, investigating basic technologies, reviewing future prospects, and determining R&D trends
- Collecting and providing information
- Coordinating exchange and cooperation: for example, the annual Micromachine Summit (first one in March, 1995) and the annual International Micromachine Symposium (beginning November 2000)
- Providing university grants: ¥3M/2 years
- Promoting standardization: through studying what needs to be standardized via committees, coming jointly from the center, universities, and industries. This study has been a three-year exercise. In 2002, work will begin to propose standards.
- Promotion: for example, the Micromachine Exhibition (11th annual in November 2000 in Tokyo). Promotion includes some activities with elementary school children to encourage them to pursue careers in science and engineering.

MTP AND MMC: ACHIEVEMENTS AND LESSONS LEARNED

The panel gathered opinions and analysis from many of the groups it visited and from other researchers. These analyses covered a fairly broad spectrum of opinions. Some felt that the MTP had been successfully executed and had achieved important milestones, while others felt that it had fallen short of achieving its potential and of placing Japan as the leader in research, development, and commercialization of micromachines, MEMS, and MST. Based on all the information, our panel has identified several key aspects of the MTP that it believes will have a long-lasting impact on Japanese research and development in this and other fields.

Achievements

As mentioned before, the initiation of the MTP in 1991 influenced the sequence of events not only in Japan but also in the rest of the world. Through its 10-year existence, the MTP and MMC have indeed accomplished several very important *achievements*:

- The most important contribution of the MTP was to help bring micromachine technology to the forefront of the research landscape in science and engineering worldwide. Although research in micromachining and miniature sensors/actuators had been ongoing at a low level in the United States, Europe, and Japan for some 25 years prior to MTP's start, it received neither sufficient attention nor funding to provide those interested in the field the resources they needed to have a significant impact. The MTP helped put the field front and center on the agendas of many countries. Perhaps the most significant impact of the MTP was felt in the United States, which started its own major funding efforts through DARPA in 1992, in part motivated by the establishment of the MTP. The race was on to see which region would emerge as the leader in micromachines, MEMS, and MST. Once the Japanese and the U.S. governments had initiated major funding programs, the European Union and many of its countries also acted to start a wide range of research programs. Germany, in particular, invested significant resources in a number of academic and industrial research centers to ensure that it maintained its competitive standing with United States and Japan. It is fair to say that without the MTP many of these activities would not have happened as quickly as they did. In this context, the MTP had a worldwide impact on the future of micromachines, MEMS, and MST.

- Until the MTP was started, the applications and potential usefulness of MEMS and micromachining technologies were known only in certain small communities. Most of the envisioned applications concentrated on sensors, actuators, or singular devices for use in automotive and medical applications. The MTP, through its very forward-looking and aggressive applications, raised the bar and articulated ways these technologies could be utilized in much more complex and significant "systems." Micromachined devices were defined to be no longer single components in a larger system, but were critical in implementing and building the entire system, with applications ranging from industrial processing and automation to miniature medical instruments and machines that could do wonderful things. Early in its life, the MTP built and demonstrated rather complex demonstration vehicles, like the micro-car, to illustrate the potential impact and power of micromachining technologies. The efforts raised awareness not only in the technical and industrial communities, but also for the general public who could witness for the first time the possibilities that could be explored in the "micro" domain. This domain was not only for building microelectronics and integrated circuit chips, but could be extended to build complex and sophisticated "micro" machines that could perform complicated tasks never before imagined. The MTP also informed many of the industries in Japan as to the potential of micromachines and MEMS. This is perhaps more important in Japan than in any other part of the world, since Japanese industry had concentrated for more than two decades on individual components that brought it much profit and fortune. This, in turn, made it hard for industry to look into the distant future and to envision other more systems-oriented emerging applications. It is argued that one of the shortcomings of the MTP was that it overemphasized very long-term and distant applications, like micromachines for plant maintenance, and that it should have paid more attention to more immediate commercial applications. While some aspects of this argument are true, it should be mentioned that the MTP played a significant role in focusing attention on the "whole" system applications of micromachines and thus forced researchers from around the world dare to imagine even bigger and better applications for micromachining technologies.
- Through its various R&D programs, the MTP helped develop many of the basic technologies needed for building complex systems and machines. The first phase of the program concentrated on "elemental" and component technologies, many of which were based on precision engineering and machining. Because of the "systems" flavor of the MTP, it had to pay more attention to non-planar technologies, which were being less aggressively pursued in the United States and Europe. Many of the basic technologies the MTP funded utilized "non-silicon" materials, utilized precision machining approaches like EDM and micromilling, and explored new and different assembly and packaging technologies. In addition, the MTP funded research dealing with flexible and agile manufacturing of micromachines, through small desktop microfactories that could easily be deployed and modified to suit various needs. More details on some of the developed technologies and accomplishments of the MTP in terms of milestones achieved in basic technologies will be discussed in subsequent chapters. These research programs resulted in more than 580 patents, and others that are in the pipeline. The panel believes that the usefulness and impact of some of these technologies, the knowledge generated, and the expertise developed will become evident in a more practical manner in the next 10 years. Although this is not a conclusion shared by many of our colleagues in Japan, the panel believes that time, and history, will be kinder to the achievements of the MTP.
- Finally, the MTP helped many companies establish facilities for MEMS and microfabrication technologies. This is by no means a trivial accomplishment. As mentioned above, most Japanese industries were not aware, and in some instances were not interested, in micromachining and MEMS technologies. They did not consider it a critical technology and therefore had little human or physical infrastructure to support playing a major role in the field. The MTP, partly through funds it provided and partly through the influence it exerted, motivated and cajoled industry to get into this field. As a result, many companies established research and engineering groups and provided facilities for fabricating and testing various applications of micromachines. Funds were expended to acquire

equipment and to develop processes. Research programs helped engineers become experts in the field and further advance the state of knowledge. Although the MTP is now effectively completed and the projects are finished, the fundamental changes will continue to have a long-lasting impact on Japanese R&D in the field of micromachines and MEMS. The MTP did indeed help establish a strong foundation in human resources, intellectual capital, and physical infrastructure that would not have been built otherwise.

Lessons Learned

Although the MTP achieved important milestones as summarized above, it had several shortcomings as well, and, according to some, was not executed as efficiently as it could have been to make Japan the leader in the field of micromachines/MEMS/MST. The panel was especially interested in learning as much as it could about the shortcomings of the MTP. It talked to many researchers, discussed this issue with groups it visited, and drew conclusions from interactions that panel members have had with their colleagues throughout the years, to highlight some of the lessons that have been learned from the MTP program. These lessons are not important just to our Japanese colleagues but also to government and industry throughout the world because the completion of the MTP represents the culmination of the first major multi-year government-initiated research and development program in the field of micromachines, MEMS, and MST anywhere in the world. There are important lessons to be learned from this program for ALL of us. These are summarized below:

- Many researchers in Japan feel that the MTP did not select the most appropriate applications and demonstration vehicles. The panel generally agrees with this conclusion. As mentioned before, applications were supported in plant maintenance, in microfactories, and in medical instruments. The applications were indeed very far out and forward looking, and they forced researchers to consider all the challenges involved in complex systems. However, some of the applications, especially those involving systems for plant maintenance, not only were too far out, but had limited commercial potential. Because of the very long term horizon, it was hard to convince the scientific community to pursue active programs in some of these areas. Perhaps more intermediate applications and demonstration vehicles should have been selected that could result in more immediate returns on this significant investment. It should be noted, however, that the application for plant maintenance was especially emphasized because a significant portion of the funding for MTP came from the energy related budget, which was particularly interested in ensuring the safety and operation of Japan’s energy and industrial infrastructure.
- The MTP was initiated and its projects were defined primarily by the government through a top-down process. The original definition of the goals of the project, and its execution did not significantly involve input from the scientific and research community, and where such input was sought it came primarily from industry that already had a close relationship with the government agencies that initiated it. The lack of input and involvement from the research and scientific community, especially from various academic institutions, is felt to have contributed to the less than optimum definition of MTP project goals and applications. This, in turn, alienated a significant portion of the research community who felt that they could not participate in it wholeheartedly. This is an important lesson that should be learned from the MTP. Government agencies and officials who have involvement only in government and administration are not the best source of ideas and inspiration for science and research programs. It is interesting to note that many of the current and future government programs, especially those in nano-technologies, have incorporated a large section of the scientific community. The panel feels that this is in part due to lessons learned from MTP.
- One message that the panel heard from many researchers was that one of the main shortcomings of the MTP was a failure to promote and demonstrate actual commercialization and technology transfer from research labs to the real world. As mentioned above, one of the main reasons for this is that the MTP project goals chosen were very forward looking. In addition, commercialization was not an explicit goal of the MTP and was not aggressively pursued.
- Although technology transfer and commercialization were not generally pursued as part of MTP, several companies were genuinely interested in real product development. However, in most cases it appears that neither industry nor the MTP were successful in developing a well-defined business model to guide the research and development programs. Most companies assumed that MEMS and micromachines

would develop into a business much like IC's and expected, perhaps unrealistically, that a single technology could be used to produce a range of products in very large volumes, year after year. This was clearly not the case, and the panel believes that until realistic business models are developed, the Japanese industry will continue to struggle to justify their support for MEMS/MST. In its visits to several companies, the panel sensed that because of the unrealistic initial expectations, many companies now feel that there is no real commercial market and business in micromachines and MEMS; in other words, industry has swung from one end of the spectrum to the other. This is obviously not a correct position since there indeed exist many important and profitable business opportunities in MEMS. The lesson that should be learned by industry is that it is incumbent upon government, industry, and the research community to help define and build a suitable business model for micromachines, MEMS, and MST.

- One issue that the panel heard, directly and indirectly, was that the MTP funds were distributed too unevenly to industry and that in some instances these were too little to make an impact. It should be noted that, in fairness to the MMC, there were limits on how MTP funds could be allocated. However, it is still believed that more funds should have been directed to major academic and research programs, which could in turn explore several new research areas. The uneven distribution of funds is believed to have also occurred partly because of a lack of involvement from the academic community in the early phases of project definition and selection. It is interesting to note that in 1995 the government passed the Science and Technology Basic Law that allowed the government to provide significant funds to universities to improve their facilities and establish major research centers. The result of this law has been indeed impressive and has had major impact on improving the physical infrastructure and facilities of several major universities.
- As discussed above, the MTP was primarily aimed at developing elemental technologies for building complex micromachines. It was natural for those groups involved to choose the most familiar and most readily available technologies they knew. Because the MTP was initiated by and involved researchers with mechanical engineering backgrounds, it utilized a variety of technologies primarily rooted in precision engineering. The MTP did not pay much attention to developing planar, photolithographic-based technologies that had been perfected for the manufacture of integrated circuits. Many Japanese researchers feel that more attention should have been paid to the development and adaptation of microfabrication techniques for building micromachines. These techniques had proven to be low-cost and highly compatible with large-volume and reliable production of integrated circuits, and they could prove to be equally powerful when adapted to the manufacture of complex microsystems bringing together the functions of sensing, actuation, and electronic information processing.
- Although the MTP was instrumental in developing the intellectual and physical infrastructure of those companies that were funded, it did not pay much attention to developing a widely available fabrication infrastructure that could be utilized by the larger research community. What infrastructure was developed was mainly captive to a few companies and not available to the rest of the research community. Although companies provided some services to academic groups who collaborated with them, it was not possible for others to obtain access to these facilities. This was in contrast to what happened first in the United States and later in Europe where a network of foundry facilities and some standard technologies were made available to the research community, partly subsidized by government funds. It is now clear that these foundry capabilities played a major role in expanding the user base and promoting the field beyond its initially small group of researchers to many disciplines and users who are not familiar with microfabrication technologies and do not have the resources to develop in-house capabilities. Perhaps the best example of this foundry service was that initiated at the Microelectronic Center of North Carolina (MCNC) in the United States that developed a standard surface micromachining process and provided it at an affordable price to many academic and industry groups.

It is interesting to note that Japan has indeed learned valuable lessons from the MTP program and that the research community is active enough to have already taken major steps in implementing new policies and programs to address some of these shortcomings.

SUMMARY AND FUTURE FOCUS OF THE MTP AND THE MICROMACHINE CENTER

The MTP officially ended in 2001, so what does the future hold for the MTP and the Micromachine Center that has overseen its execution for the past 10 years? Based on information gathered from MMC officials and the research community, there do not seem to be any significant funds allocated for the continuation of the MTP. The MMC will continue its operation, albeit on a much smaller scale. Some residual funds are available through the government and through an endowment to continue some activities, primarily in the areas of dissemination of knowledge, education and outreach, and a recently started program in developing standards. The technologies developed through the MTP will continue to be disseminated to a variety of potential customers. Some future efforts will be aimed at new applications for these key technologies. MMC will continue to bridge existing and potential future technologies and will look for specific new applications. Microfluidics is one of these specific applications, while others are in the information technology area and in environmental applications.

Current Climate

Before discussing current and future government initiatives in funding new science and engineering programs, it is useful to assess the existing environment in the research and scientific community, as well as the government and industry. This environment has been the result of many factors, some global, some regional, and some the result of research programs of the past decade in micromachines and MEMS in Japan. As mentioned above, the experiences learned from the MTP have already had some influence on the Japanese research and development landscape.

- As the panel visited with various groups, it quickly became clear that one of the most important factors that is shaping the Japanese government science funding policies is the announcement of the U.S. National Nano-technology Initiative (NNI) started by the Clinton administration in 1999. It was interesting to observe that the launch of NNI has raised awareness and mobilized the Japanese government to act and provide funding for this very important emerging field. In Japan, a clear sense of urgency exists since the United States is investing a major amount of funds in the broad area of nano-technology. Japan must do the same to maintain and re-establish its leadership position in basic science and technology. The Japanese scientific community clearly feels that this is a critical moment and that the government and industry cannot afford to hesitate. It must become an active participant. It is somewhat amusing to see that history seems to repeat itself, although through a reversal of roles. The competitive pressures that we all experienced in the United States in the late 1980s in the area of semiconductors and microelectronic products such as DRAMs and the sense of urgency our community felt in the early 1990s when MITI launched the MTP, triggered the U.S. government to launch several programs of its own, one of which was DARPA's MEMS program. Now, some 10 years later, the U.S. NNI has triggered the government and research community in Japan to act and provide significant funds to Japanese industry and academia to secure Japan's place in the emerging high-tech areas. Industry and academia feel that Japan cannot continue to depend on the traditional markets of semiconductors such as DRAMs as these markets are being increasingly taken away by other nations in Asia. It is felt that Japan must explore and invest in new areas and that micro and nano-technology will play a critical role in the future and thus should be one of these areas.

Therefore, the U.S. NNI and other nano-technology-related activities in Europe have helped set the stage for many programs that we will likely see from the Japanese government now and in the future. However, the panel also observed many other changes that it feels have been brought about by the experiences that were collectively learned from the MTP.

- First, it is clear that many of the current and upcoming government-funded programs have been driven by the research and academic community and that the champions of many of these programs are researchers, often professors, who understand the basic scientific and research needs and who are very effective in promoting them at various government levels. There appears to be a much closer interaction between government agencies and the research community. This close interaction has indeed helped these programs to be more readily accepted and will likely be more effective when they are completed.

- Second, Japan seems to have adopted the U.S. model of funding focused research and application areas of MEMS and MST with more near-term commercial applications. Many of these programs have a well-defined goal, are funded by various government agencies with a specific mission in mind, and include both universities and companies.
- Third, it appears that many of the recent research programs have funds awarded to major academic groups that have demonstrated their capabilities in a given area of research. This is somewhat different than what has been traditionally done in Japan where government funds were distributed evenly, often due to political pressures, to university programs irrespective of their qualifications; this distribution resulted in a large number of under-funded programs, none of which could have a major impact. The current model is certainly preferred since it allows at least a few research groups to reach a critical mass and be able to make significant advances. This is especially true in the area of MEMS and microsystems, where significant infrastructure and facilities are needed to carry out fundamental research.
- Fourth, there seems to be a clear interest in major activities, primarily by university faculty, to develop foundry services and establish a distributed manufacturing capability for MEMS and MST. The research community has correctly realized that without such an infrastructure, MEMS and MST will not be able to become widely utilized and that without a diverse user base the field will eventually die. It is interesting to note that many of the companies that had established facilities through funds provided by MTP have started to offer these facilities as a foundry to companies interested in manufacturing and commercializing MEMS and MST. A more detailed discussion of these activities will be presented in a later chapter.

To summarize, the current research and funding environment in Japan is very active and forward looking, and in many ways Japan has adopted policies and approaches practiced in the United States. There is a sense of community developing, and although there is a sense of urgency, there also appears to be a sense of optimism and involvement that the panel had not seen over the past 10 years.

Applications and Government Initiatives

The research and science community has identified a number of application areas for micro and nano-technologies and has argued that these be the drivers for future government funding programs. These areas include the life sciences, environmental protection and monitoring, combinatorial and analytical chemistry, and information technology. Collectively or individually, these applications encompass and drive many other applications that will affect many aspects of society. At the root of many of these applications are the basic science and technologies at the nano level that will help pave the way for improved understanding and development of new materials, new manufacturing technologies, new knowledge of the biological systems and their applications, and fundamental understanding at the molecular and atomic levels necessary for future development efforts. It is believed that micro technologies play an equally important role in that they facilitate the development of practical uses of nano-technologies and ultimately enable the realization of the application areas defined above. As such, there is a strong feeling that micro and nano-technologies go hand in hand and that one cannot realize its potential without the other.

Because of this, many of the emerging programs have a combined focus on nano-technology and its applications. The research community has used this basic approach as a way to convince government to launch new programs in micro and nano-technologies, many of which have a significant component involving MEMS and MST. The panel did not seek to specifically identify government programs and their exact funding level and detail. What information we gathered was based on information collected throughout our discussions with various groups we visited. Based on this information, there are several programs that have either been approved, or are close to being approved, for funding and initiation:

- Perhaps the most notable program that has received approval from the government is funded by the Ministry of Economy, Trade, and Industry (METI) in the general area of microfluidics, and with a specific focus on Microchemical Analysis and Synthesis Systems. This program is to start in early 2002 with a level of funding between $50-100M for five years. The leading champion of this program has been Prof. Kitamori from the University of Tokyo and KAST. Several of the sites we visited will also take part in this activity. It is interesting to note that the project is focused and has specific commercial applications and that the academic research community is well tuned to the need for commercialization of the results of research funded under this program.

- In addition to the METI program, an initiative entitled Microfluidics for Cell-Based Biochemistry will likely be funded by the Ministry of Agriculture in 2003. The funding level for this program was not precisely defined and therefore is not cited here. This program is also focused and is more closely aimed at the application of microfluidics in biology and biological systems.
- For the past two years, a group of researchers led by Prof. Esashi at Tohoku University have been promoting the initiation of a research and development program in micro power generation. Prof. Esashi's group has been one of the leading programs in Japan working in this area and has already reported some of the most important accomplishments in this emerging field worldwide. At the time of the writing of this report, the program was still being developed; and the panel could not determine whether the government has approved funding for the program. However, there was a feeling on the part of several researchers that funding for this program will be likely available, but it will tied to funding within the nano- technology initiative. If funded, the program will likely start in 2002/2003 time frame.
- Although not specifically aimed at funding MEMS and MST, a government program directed at intelligent transportation systems (ITS) has provided some funds to carry out research and development on microsensors and microinstruments with the specific application in ITS. Sensors play a significant role in ITS and it is likely that various programs in this area will continue to fund research activities in some aspects of MEMS and MST.
- As mentioned above, the academic community has correctly identified the need for establishing strong foundry and distributed manufacturing services within Japan, and it is lobbying the government to provide some funds to subsidize some of these activities, at least through the initial phase. It was not clear if such funds will become available, but the academic community has been able to strongly argue the importance of this area to the government. The panel feels that the establishment of such a foundry capability is instrumental to the future of the field in general as well as to a leadership position for Japan in MEMS and MST. It is worth noting that several of the Asian Pacific nations such as Taiwan and Korea are pursuing their own activities in this area and unless the Japanese government provides a helping hand now, later actions may prove futile.
- Finally, the panel noted that there is little funding activity planned for the areas of RF and optical MEMS. This was somewhat surprising given the fact that these two areas have received much attention and funding in the United States and Europe.

FUTURE OUTLOOK AND SUMMARY

Japan is indeed at the threshold of a new era of research and development in the fields of MEMS and microsystems. The MTP era is over, and the National Nanotechnology Initiative has heralded the dawn of a new era in Japan and the rest of the world. The panel feels that the outlook for nano-technology is quite positive in Japan; this has been partly brought about by the launch of the U.S. NNI. MEMS and microsystems technologies are believed to be a critical part of realizing the promise of nano-technology, and as such many of the programs funded now or in the future will have a MEMS/MST component in them. For now, biotechnology and analytical chemistry drive many of the government-funded programs. Micro power generation is next on the list and will likely receive funding. There is little activity in the areas of RF and optical MEMS. In all these current programs, and in many future programs, we will very likely see a strong emphasis on developing products, commercialization, and technology transfer from university research labs to existing companies, as well as to new start-ups.

The panel feels that the future outlook for Japanese research and development in MEMS and MST can be quite bright and positive only if all parties involved (government, industry, and academia) understand that there is great commercial potential in these fields and that this potential can be realized only if they continue to closely interact with each other in a unified fashion. Japan cannot afford to let this opportunity slip through her fingers.

CHAPTER 3

INDUSTRY AND UNIVERSITY INTERACTIONS

Elliot E. Hui

INDUSTRIAL SUPPORT OF UNIVERSITY RESEARCH

In Japan industrial funding of university research in microsystems is small compared to government funding, a situation that is similar to that in the United States. However, the interaction between industry and academia is evolving in Japan. The broadly themed joint program, in the mold of the Micromachine Technology Project, appears to be making way to more focused collaboration on specific tasks. The newer models also result in more direct building up of university facilities and programs.

The recently completed Super-Eye Image Sensor (SEIS) project of the Osaka Prefecture is an example of the classic joint program. The project involved the participation of Osaka University and 13 companies from the prefecture. The five-year project received $4.25 million, with 60% of the funding coming from industry and 40% from the prefecture. There was limited investment in the research facilities of the university, however, because the funded facilities were built away from the campus. In addition, only three researchers and five students from the university were funded, in contrast to 32 company engineers.

In addition, the funding was diluted among the participating groups over a diverse range of projects including sensors for infrared, flavor and smell, acceleration, humidity, and magnetic field; ultrasonic and differential-wavelength imaging; and basic silicon process technology. Splitting the project funding over such a large number of companies and broad diversity of projects would seem to limit the effectiveness of the SEIS project in impacting the R&D agendas of any single participating group.

In contrast, the panel observed a number of examples of more focused collaboration on a specific project between a company and a university research group. The Esashi group at Tohoku University has a large number of such collaborations, in which participating companies often have a specific product in mind for development. For example, Tokyo Electron is supporting a probe card for VLSI testing, and Tokimec is collaborating in the development of a gyroscope and accelerometer.

The usual mode of collaboration is that a company will send an actual engineer into the university research lab to work for a couple of years on the project, and then the engineer will return to the company, bringing his expertise as well as the prototype design. These collaborations are a significant source of funding for building up and maintaining the university research facilities themselves. Of the $1 million of funding required each year to maintain the excellent facilities at Tohoku, half is provided by industrial support. The national government provides the other half.

Such collaborations also abound in the Fujita group at University of Tokyo. For example, Renault-Nissan supports a 2-D optical scanner, and Anritsu is involved in developing a device for optical fiber diameter measurement. In addition, Olympus is pursuing collaborative projects in biological applications of microsystems with a number of different universities, apparently because the head of their microsystems division had a positive experience while personally working at Tohoku.

Finally, in a style of university-industry collaboration common in the United States, Ritsumeikan University has recently formed a consortium of companies to support microsystems research there. Fifty member companies, mostly from the Kansai area, pay $1000 per year in exchange for regular seminars and research reports. Such an arrangement benefits the university because it represents a regular source of funding for research and infrastructure. The benefit to the companies is not quite as direct, but it should be noted that Ritsumeikan also hosts many visiting engineers from industry. A final note is that the $1000 per year rate is low by U.S. standards. For example, in the Berkeley Sensor and Actuator Center, 30 companies each pay $50,000 per year for consortium membership. The strategy of Ritsumeikan at this stage is to encourage participation from as many companies as possible.

EDUCATION AND KNOWLEDGE TRANSFER

The quality of Japanese university research programs in microsystems is world-class. The future success of the microsystems industry in Japan will depend in large part on its ability to bring this expertise into company R&D laboratories. Of greatest importance is the positive effect of having industrial visitors work directly within the university labs, a model common in Japan that is rarely practiced within the United States.

The quality of student education in microsystems is uneven across Japan. The strongest program observed was at Ritsumeikan University, offering four graduate courses for a comprehensive foundation in the field. Courses are offered in materials, processes, devices, and systems. Student interest is very strong, with 80 students enrolled in each class. However, each course is offered only once every two years, and since students usually try to finish all their coursework in their first year, most students take only two of the four courses.

Waseda University offers both graduate and undergraduate coursework in microsystems. It is important to note that in one undergraduate course, students have the opportunity to design an actual device on a multi-project wafer, which is then fabricated by an informal foundry service utilizing industrial facilities.

In contrast to such strong examples of teaching, however, the panel observed that other universities offer no courses at all in microsystems. In addition, interest in microsystems was low within the general student body at some universities, including at Tohoku University. Perhaps surprisingly. university-level teaching in the area of microsystems is also not fully developed at this point in the United States, but the situation is still somewhat stronger than in Japan.

On the other hand, Japan holds a strong lead in microsystems education within the K-12 population. There is a general push to increase interest in science and technology among Japanese youth. For this purpose micromachines offer an advantage, being visually appealing to a broad audience and particularly intriguing to a group fascinated by robots. Over the course of the Micromachine Technology Project, a drawing contest was carried out among elementary school children, with 2000 pictures being submitted each year to the Micromachine Center. In addition, Prof. Fujita has played a large role in a public exhibit in the Museum of Emerging Science and Technology in Tokyo, which includes hands-on demonstrations of microsystems. Additionally, Ritsumeikan University holds microsystems seminars and open houses for the secondary schools within the Ritsumeikan educational system.

The primary mode of university knowledge transfer in the United States is the education and training of students who then graduate and become employed by companies and thus bring academic expertise into industry. In contrast, the university research labs in Japan have a proportionally fewer number of graduate students but a much greater number of visiting industrial researchers. There are fewer Japanese graduate students; so in order to provide the manpower to carry out their research, professors rely on industrial research associates as well as foreign researchers. In visits to university labs, the panel encountered visitors from various Asian and European countries. Visitors from the United States are much less common.

In Japan then, knowledge transfer to industry often takes the form of a company employee spending a couple of years within a university lab working on a project that the company is specifically interested in. Often, an engineer with expertise in a field other than microsystems will come to a university lab to learn the technology. For example, an optics expert may come to learn microfabrication and then develop a MEMS optical switching system. It is the opinion of the panel that this type of university-industry collaboration is highly effective, and the United States would benefit from increased use of this model.

In Japan, the panel also observed examples of other forms of industrial education common in the United States, such as research conferences for consortium members at Ritsumeikan as well as industrial short courses, such as the well-attended course at Tohoku University.

COMMERCIALIZATION OF UNIVERSITY RESEARCH

The Micromachine Technology Project has generated few commercial products. On the other hand, the project was never intended to be commercial. The funding climate in Japan has changed today, however, and now the measures of success for research funding definitely include commercialization.

In the United States since 1980 when the Bayh-Dole Act was passed, university inventions licensed to the private sector have spawned over 2,200 new companies that generate about $30 billion in economic activity every year. In light of this apparently tremendous success, Japan is trying to learn from what is perceived to be the U.S. model—university inventions licensed to the private sector that spawn new companies. Changes in Japanese law now allow for and encourage the formation of technology licensing offices (TLO) at universities, bringing academics to a level of commercial involvement previously unheard of, seeing as professors are regarded as public servants.

Almost every university the panel visited has formed a TLO in 2001. Although a couple of professors sounded very enthusiastic about patenting and licensing, the concept of the TLO seems rather unfamiliar to most academics in Japan. Many of the new TLOs were being funded for the first few years by government supplements. They seemed to be expected to be self-sufficient after that time, but it was unclear whether the TLOs would become viable in such a short period of time. The level of funding of the TLOs was also rather low, raising the question of whether a significant number of patents could be filed.

Even in the United States, the effectiveness of the TLO in promoting the transfer of technology into industry is itself a continuing topic of debate. The desire of a university to patent and profit from its research can come into conflict with the interests of companies involved in collaborative research efforts. The Esashi group at Tohoku University has a long history of commercialization in the area of microsystems and has developed an “open” policy to deal with this issue. If an industrial visitor comes into the lab bringing ideas, the company is asked to patent anything they wish to before the employee enters the lab, because once in the lab, researchers share all information freely. The intellectual property coming out of research developed within the lab is shared jointly between the university and the company.

In the Fujita lab at the University of Tokyo, university licensing has yet to really gain momentum. Researchers and professors own their own intellectual property and write their own patent applications if they so desire. Where significant national resources have been utilized for the development of a device, the government retains the patent. At Ritsumeikan, the system for handling intellectual property seemed most familiar from a U.S. perspective, a comment that could also be made for practices there in general. Intellectual property is split evenly with a third going to the researchers, a third going to the university, and a third going to the TLO. A professor has the opportunity to pursue his own patent, but he would need to individually provide the funds in that case. In the case of industrial visitors, intellectual property is split evenly between the company and the university.

On the subject of commercialization, it should be noted that the Esashi group at Tohoku has had a history of successful technology transfer dating back to the 1970s, well before all of the recent increase in attention in this area. Devices that have been successfully brought to market include an ISFET pH sensor marketed for use in home aquariums, a capacitive pressure sensor, and an enzyme biosensor for detecting pyroli bacteria, the cause of many stomach ulcers. Currently Tokimec, a manufacturer of navigation-grade gyroscopes, is preparing a levitated-mass gyroscope for market.

With its strong history, Tohoku University has been forging ahead recently with the beginning of the New Industry Creation Hatchery (NICHE), a novel concept for a Japanese university. The focus of NICHE appears to be laboratory research conducted towards product development, receiving guidance through an industrial liaison office and benefiting from the intellectual input coming from the graduate-level studies within the university. An early fruit from this effort is a spin-off company being formed by a medical doctor to commercialize a steerable catheter made of shape-memory alloy.

Although university-bred startups in microsystems have been very common in the United States, particularly recently, few startup companies have come out of Japanese universities. Nevertheless, Professor Sugiyama at Ritsumeikan has recently formed a company to broker a foundry system for microsystems manufacturing.

Another example is the Institute of Microchemical Technology (IMT), founded by Professor Kitamori from the Kanagawa Academy of Science and Technology (KAST). This company markets the Thermal Lens Microscope and the microfluidic chips developed in Kitamori's research group. Over the past few years, KAST has spun off six companies from its research labs in an attempt to recoup some of the prefecture's research investment. The goal of IMT, however, is not to make a large profit for itself through large-scale manufacturing. Instead, the goal seems to be to give back to the prefecture by selling instruments to other companies, thus accomplishing technology transfer.

In summary, the commercialization of university research in microsystems is now an important goal for Japan. There is a desire to duplicate the entrepreneurial activity found in the United States through the licensing of university intellectual property although most of these efforts are not yet ripe and their effectiveness remains to be seen.

CHAPTER 4

FOUNDRIES AND INFRASTRUCTURE

David J. Monk

INTRODUCTION

Before discussing the foundries and infrastructure in place in the Japanese MEMS industry, it is instructive to describe the industry's background in Japan. There are two important points about the semiconductor industry that have influenced Japanese MEMS infrastructure. First, business has become much more global. The last WTEC (formerly JTEC) review of the Japanese MEMS industry was completed in 1994 (Wise et al. 1994) following a decade of nationalistic dominance in the semiconductor industry by Japan. However, the decade of the 1990s saw much more global business. Many corporations are multinational, especially in Asia, North America, and Europe. This expansion of business has changed the way international business and technology are developed.

Second, the industry jargon reflects the origin and focus of the technology. In Europe, the industry is generally called "Microsystem Technologies" (MST). In the United States, it is "Micro-Electro-Mechanical Systems" (MEMS), while in Japan, it is called "Micromachines." The subtle difference, especially between the United States and Japan, results from the roots of the industry. In Japan, initially, micro- and milli-machining were developed in response to the Micromachine Technology Project and were largely started in the mechanical engineering field. In the United States, MEMS technology was developed, at least initially, mostly by electrical engineers from the semiconductor industry. A decade has made the topic much more cross-disciplinary, but the beginnings have affected the thought process and infrastructure that has developed.

This section on foundries and infrastructure is divided into two major areas: the first on technical development infrastructure and the second on business development infrastructure. Further subsections are meant to illustrate functional areas that are required for product development with MEMS- or micromachine-based products.

TECHNICAL DEVELOPMENT INFRASTRUCTURE

MEMS product development includes a significant amount of technical infrastructure from design to fabrication and packaging/testing. The following section describes progress in the Japanese MEMS industry in each of these functional areas.

Design and CAD Tools

The design methodology throughout the global MEMS industry, and Japan is no exception, still tends to be ad hoc. This is especially true when contrasting this process to the design of an IC. Typically, an IC design process would include: architecture development, architecture (or high-level) modeling, specification definition, process parametric model extraction, library development and tool establishment, schematic development, target simulation, "corner" simulation (or sensitivity analysis), floor planning, layout, verifications (layout vs. schematic, design rule check, etc.), mask preparation, and silicon/simulation validation. Depending upon the sophistication of the design effort, these process steps may also be repeated multiple times or omitted, if re-use is being followed.

However, in the MEMS industry, in general, architecture development usually occurs through trial-and-error. Specifications may not include all required parameters as a result of inexperience with a particular device. Furthermore, there is very little mechanical material property parametric analysis, and few good mechanical parametric libraries are in use. Layout is a very manual process, and validation of the design including feedback to future design process is not systematic. There is evidence of use of CAD tools within the industry in Japan, as there is in the United States. For example, during the development of the Omron pressure sensor, finite element analysis (FEA) was used extensively (Horiike et al. 2001). Finite element analysis was used to analyze the impact of adding a post to the center of a diaphragm. The goal was to minimize the effect of nonlinearity by providing more consistent average deflection across the diaphragm (Fig. 4.1).

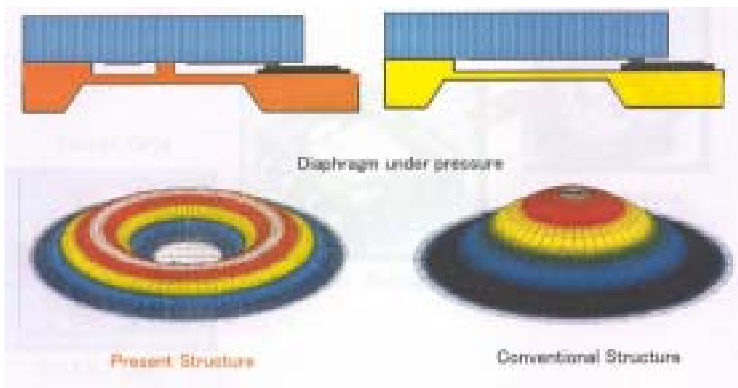


Figure 4.1. Omron finite element analysis on an absolute pressure sensor. The goal was to provide better linearity performance for the device (Horiike et al. 2001).

Other groups also used FEA tools: in addition to Omron's use of ANSYS, Waseda University was using ANSYS and Coventor, and Toyota Central Research and Development Labs (CRDL) was using NASTRAN.

Toyota CRDL collaborated with several U.S. groups in an NIST-sponsored round robin to evaluate polysilicon fracture strength. Figure 4.2 shows an example of the structure Toyota CRDL is using to make the measurements.

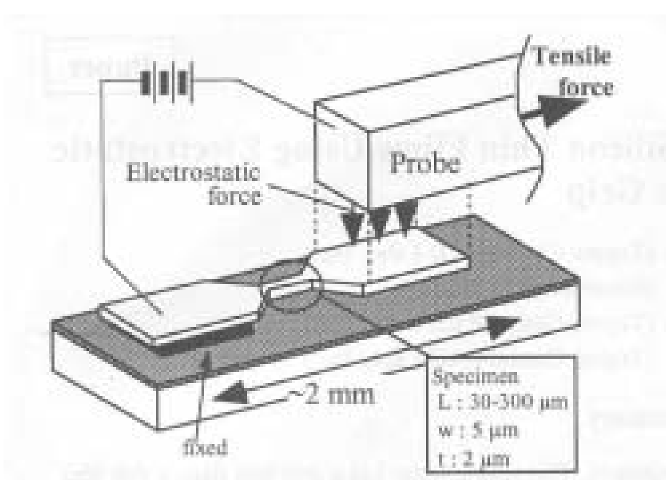


Figure 4.2. A dog-bone-shaped polysilicon fracture strength test structure being used by Toyota CRDL to provide some material property data on polysilicon for the design process (Tsuchiya et al. 1996).

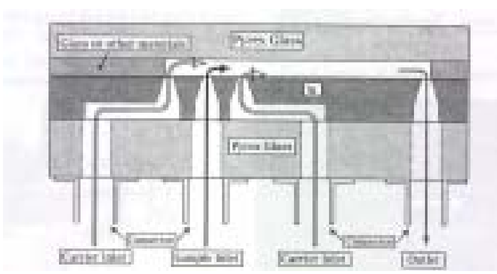
However, there is very little evidence of an integrated design flow that includes tools to go from architecture development to silicon. The MEMS design process being used in Japan, and in the United States to a large extent, appears to be a “build and test” approach.

MEMS Fabrication Technologies: Development and Production

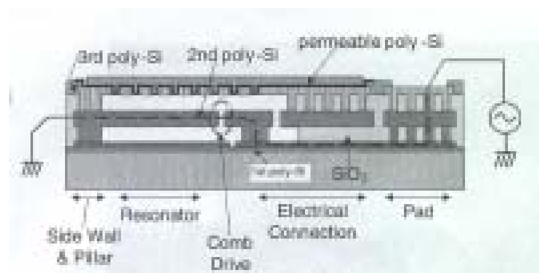
Perhaps because mechanical engineering has influenced the MEMS industry in Japan, the processes being evaluated for MEMS and Micromachine applications are varied and much less silicon-centric than in the U.S. MEMS industry. Figure 4.3 shows four figures that exemplify this.

The so-called “standard” MEMS processes of bulk micromachining (Fig. 4.3a) and surface micromachining (Fig. 4.3b) are in practice in Japan. In Figure 4.3a, Waseda University is using bulk micromachining and wafer anodic bonding to create a microfluidic cell. In Figure 4.3b, Toyota CRDL is using three-layer polysilicon surface micromachining to produce an angular rate sensor.

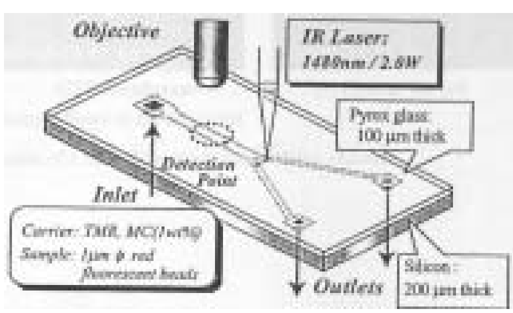
However, the Japanese appear to be much more willing to explore non-standard semiconductor processes and materials. Figure 4.3c is an example of a polymer being used in microfluidics. In this case, the gel material is embedded within the fluidic channel. Upon irradiation from a laser, the gel goes through the gelation phenomenon, which blocks the fluidic channel, thus allowing a fluidic switch. Furthermore, Figure 4.3d shows an example of the use of a ceramic material for ultra-high temperature applications. In this case, Tohoku University is using sintered silicon carbide to create a micro-combustion engine.



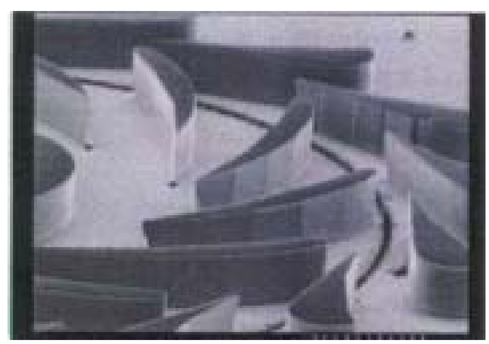
(a)



(b)



(c)



(d)

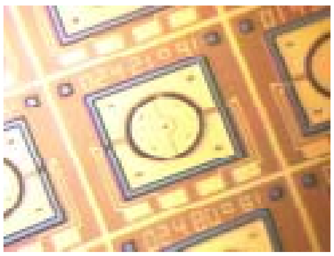
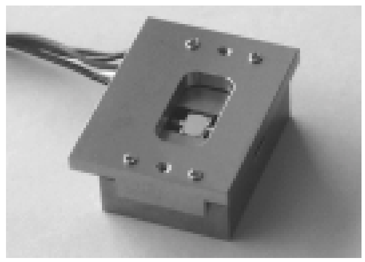
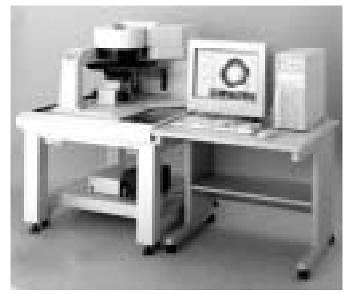
Figure 4.3. A variety of MEMS materials and processes are in use in Japan. (a) Bulk micromachining and wafer bonding (Tashiro et al. ND); (b) Surface micromachining (Tsuchiya et al. 2001); (c) Polymeric materials exhibiting the gelation phenomenon during operation (Tashiro et al. 2001); and (d) Sintered ceramics for high-temperature applications (Tanaka 2000).

Additional details that show the variety of technologies used in the Japanese MEMS industry will be presented in Chapter 6. Ultimately, as a result of the mechanical engineering influence on Japanese MEMS/micromachining industry in contrast to the semiconductor-based electrical engineering approach that is used in the United States, solving product development problems by employing a variety of processes and materials is more flexible.

Interface ICs, System Partitioning, and Integration

There was very little discussion of interface analog or mixed-signal ICs used with MEMS-based products in Japan. Omron discussed the value of surface micromachining and CMOS integration as a way to improve return on investment and presented the Analog Devices ADXL series of accelerometers as an example. Murata discussed their plans to integrate multiple (inertial) sensors into a sensor cluster device. Their approach, however, was not through integration on silicon but through a system-in-package.

There were, however, several instances where MEMS was used as the "golden screw" for a product. For example, the Olympus laser-scanning microscope (LSM) utilizes an optical MEMS-based scanner. Figure 4.4 shows the levels of integration and system partitioning used to create this LSM.

(a) (b) (c)

Figure 4.4. The Olympus laser-scanning microscope (LSM): an example of a MEMS-enabled product. The MEMS device is a very small portion of the system cost, but it provides the capability for the equipment to function (Katashiro et al. 2000). (a) The optical MEMS device. (b) The packaged scanner. (c) The Olympus OLS1100 LSM.

Other examples of MEMS-enabled products include some of the features on the Sony Aibo dog. This toy can right itself after falling over as a result of the MEMS gyroscope that is embedded in the product. Also, Hitachi uses some microfluidic devices to enable a water-filtering product.

Research and Development Facilities

Several types of MEMS research and development facilities can be found in Japan. Companies like Murata, Toyota CRDL, and Omron use a centralized R&D lab for their development work. There are industry-academic collaborations, including Waseda University and Olympus in microfluidics and Tohoku University and a variety of companies. Tohoku University is employing a "slim" philosophy to acquire tools for lagging edge technology (3") and yet maintain close to state-of-the-art tools. This augments their older labs where homemade equipment is plentiful. Other new R&D facilities have appeared at the University of Tokyo IIS and are planned at Waseda University and Ritsumeikan. But, the mainstays in Japan for academic R&D facilities are "drop in" fabricating labs (fabs) that are built within existing buildings. The most telling example of this was a broom closet that had been converted into a photolithography room at Waseda University. The Japanese appear to be much more willing to "build their own" than Americans. Perhaps this is because the American MEMS industry emerged from the semiconductor industry where industry-standard tools were already present. Instead of buying tools, the Japanese are willing to build them. The Japanese tend to espouse the philosophy that we saw under a homemade reactive ion etch system in the old fab at Tohoku University: "don't worry just try."

Foundries: Development and Production

Foundries for MEMS have been slow to develop within Japan. In the United States, it was recognized much earlier that foundries were essential for the commercialization of MEMS products. This may, again, be the result of the U.S. MEMS industry emerging from the semiconductor industry where the foundry-culture had already been established. In Japan, the "job shop" mechanical engineering culture is much more prevalent. Nevertheless, the Japanese are realizing the need for MEMS foundries: to minimize long development cycle times, to maximize return on investments, and to improve the innovation process by providing facilities for manufacturing development devices. While some foundries are being established in Japan, there still is a need for a foundry infrastructure organization to direct use to the appropriate foundry facilities (e.g., like the MEMS Exchange in the United States). Professor Sugiyama of Ritsumeikan University is starting a company poised to provide such a service.

Several notable foundries have begun service in Japan for the MEMS industry. Omron is advertising the capabilities shown in Figure 4.5. This fab has been in place since 1975 and employs 230 people with separate capability for bipolar and MEMS. The strategy at Omron with this fab is to fill the existing capacity and "harvest" benefits from the established bulk micromachining capabilities that are used to produce pressure and acceleration sensor products today (Fig. 4.6).

Figure 4.5. The Omron foundry service for MEMS (Horiike et al. 2001).

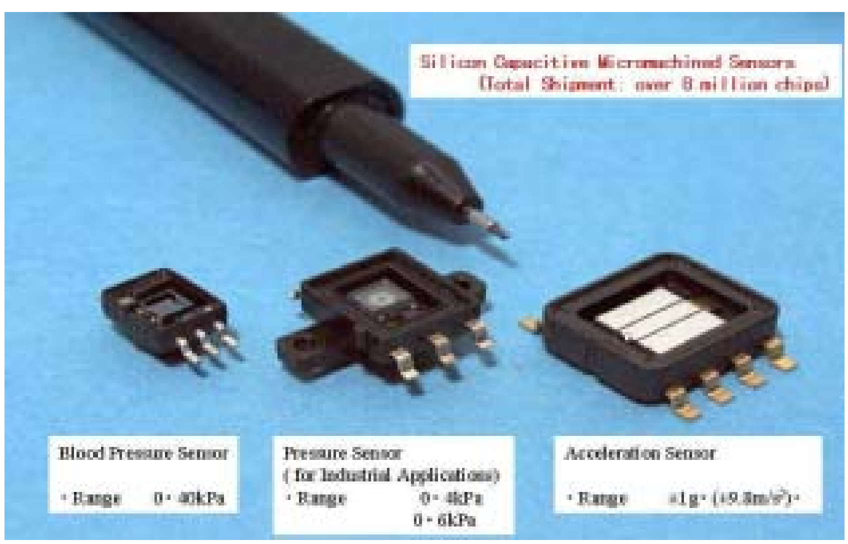


Figure 4.6. The Omron foundry strategy is to augment production demand that is also being used to produce these pressure sensors and accelerometers (Horiike et al. 2001).

Similarly, Olympus just announced their 4" foundry service at the Micromachine Exhibition in Tokyo from 30 October to 2 November 2001. They, like Omron, are interested in augmenting production demand. At present, their MEMS fab produces small volume production for optical MEMS devices (e.g., for the LSM).

However, unlike Omron, Olympus is advertising a “turnkey” operation that will include design, prototyping, and production. Production capability includes the following: project aligners, I-line steppers, double-sided aligners, thin film deposition, electro-plating, dry etching—including DRIE, wet etching, wafer bonding, testing, and packaging.

Other MEMS foundries in Japan that were not visited explicitly but were discussed with users during the site visits, include the following:

- Sumitomo (6” surface micromachining)
- Dai-Nippon Screen Printing (surface micromachining)
- Yokogawa (surface micromachining)
- Sony USA-San Antonio (http://www.foundry.sony.com/default.shtml: 6” MEMS-capable facility for surface, bulk micromachining)
- Ritsumeikan (LIGA)

Also, several groups remarked on the development of MEMS foundries within Taiwan.

Finally, although the Japanese are following the lead of the United States and Europe and developing MEMS foundries, there is a capability that the United States (and possibly Europe) could follow the lead of Japan in developing: specific, low-cost, fast turnaround plastic microforming and similar job shops. Several of these small companies in Japan are becoming much more available for work as the keiretsu groups become more loosely organized.

Backend Technologies: Package, Test, and Reliability

Backend technologies tend to be much more proprietary within the global MEMS industry. It has been well documented that MEMS devices must be designed in concert with their packaging because packaging can affect device performance. This appears to be recognized in the Japan MEMS industry as well; hence, few are willing to discuss details of these processes. Nevertheless, a couple of new techniques were described for packaging MEMS. Murata is using a vacuum packaging technique that includes sandblasting through anodically bonded Pyrex to create vertical feedthroughs. It is also considering multisensor packaging to create inertial sensor clusters. Moreover, the University of Tokyo IIS is performing work on interconnection enabled by micromachining techniques. Figure 4.7 shows an example of a “rack” of silicon-based devices that are interconnected in a process akin to circuit-board packaging.

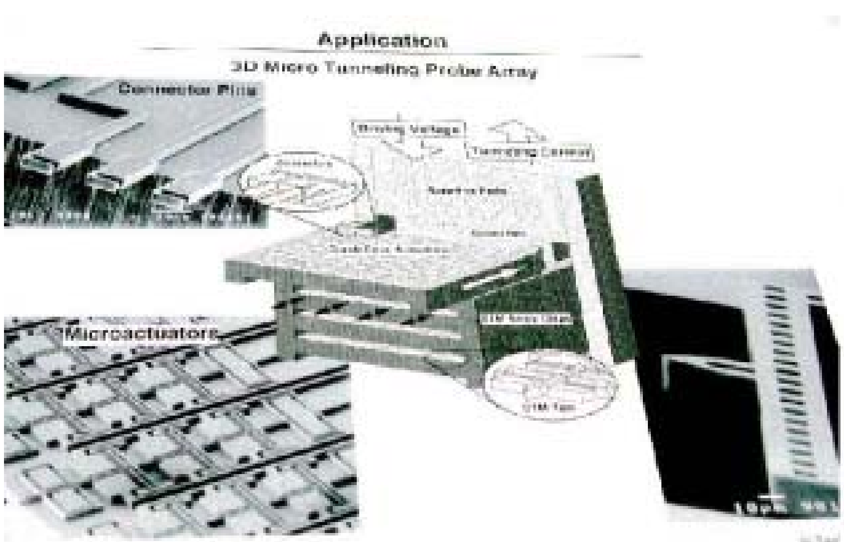


Figure 4.7. A packaging technique for mounting multiple silicon devices together that is enabled by micromachining techniques (Berlin et al. 2001).

While there is little published about MEMS packaging, even less is published about MEMS tests and/or reliability. The conclusion that is drawn about this is that most companies, like those in the U.S. MEMS industry, typically keep this technology proprietary, e.g., as a trade secret.

BUSINESS INFRASTRUCTURE

Product development and commercialization involves an equally elaborate business development infrastructure. This section will describe some of that business infrastructure. It does not go into details on business operations, marketing, and sales, as those are left for such conferences as the series "Commercialization of Microsystems" to address.

Funding Sources

Funding sources for R&D in Japan are varied, but they include the notable absence of venture capital funding. Few startups exist in Japan, so R&D funding is generally either based in large companies and funded internally (e.g., Hitachi, Sony, Murata, Olympus, Omron); a joint company-academia arrangement (e.g., Tohoku University and Toyoda Machine Works and their ISFET development or Tohoku University and Ball Semiconductor and their spherical 3-axis accelerometer); or government-based (e.g., through the Micromachine Center/Micromachine Project or through Prefecture Funding). Two substantial differences in government funding regulations in Japan are that Japanese R&D funding is not used for funding students and that approximately 90% of it can fund facilities. This is contrary to the approach in the United States where government funding cannot be used to fund facilities, and it is used to a large extent to fund students.

International Interactions

As was mentioned in the introduction to this section, international collaborations are much more prevalent in 2001 than they were during the late 1980s/early 1990s. Two significant categories of international interactions were identified. The first are marketing arrangements. For example, Wacoh out sources much of its sales and marketing functions to the MEMS manufacturer with whom it out sources its production. Wacoh is actively seeking global partners (especially in the United States) for similar arrangements. Other groups, like Omron, are multinational corporations that have significant sales and marketing presence in the United States already.

A second type of collaboration is on the academic level. The former Mechanical Engineering Labs in Japan is currently hosting several researchers from outside Japan (China, Korea, and Singapore, to note a few). Also, Professor Fujita et al. at the University of Tokyo have developed a Center for International Research on Micromechatronics (CIRMM) with CNRS in France. In fact, several professors commented that they add to their research core with industrial employees from around the world (e.g., Prof. Esashi at Tohoku University has researchers from Germany at present). It was notable, however, that during the 17 site visits, we did not notice any U.S. researchers in the Japanese labs.

Intellectual Property

Intellectual property is becoming a much more important factor in commercialization, both in the academic ranks and in the MEMS industry. Several universities that were visited are initiating technology licensing offices. Among those that are starting this practice are Osaka University, Tohoku University, and Waseda University. It is likely that others will follow suit. This is a direct result of following the lead of U.S. universities that began this practice in the 1980s.

Nevertheless, groups like Tohoku University state very clearly that they have an "open" policy for IP sharing. At places like Tohoku and University of Tokyo IIS, the unwritten policy appears to be for industrial researchers to file background IP prior to beginning their tenure on campus. Any IP that results from their work at the university is jointly held by the company and university.

A unique company in Japan today is Wacoh. First, it is a startup, which is rare in Japan. Second, the business model that is followed is one that relies on intellectual property. Wacoh's business performance, which has always been in the black, includes revenues from licensing, outsourcing of manufactured products, and royalties. The business was set up specifically for this purpose. The proprietor, Okada-san, started the first phase of his business by obtaining more than 100 patents. Once these were in place, he began working with outsourced manufacturing sites to develop products. This is one example of a U.S.-style start-up. When asked why there are not more such businesses in Japan, Okada-san recited business laws in Japan that state that one's personal finances are not completely separate from corporate finances. So, corporate bankruptcy also means personal bankruptcy. Furthermore, personal bankruptcy results in the loss of some civil rights, like the right to vote.

Standardization and Information Exchange

As in the United States, there are very few MEMS standards in Japan. As described earlier, there is even a wider range of fabrication technologies and several small-volume niche markets. And, backend processes are generally considered proprietary, so they are not usually open for standardization discussions. Nevertheless, the Micromachine Center has recognized this issue and has dedicated part of its resources to promote standardization. In fact, standards for thin film materials testing methods are being proposed during 2002, following a three-year exercise on the subject. Detailed information can be found at the MMC website: http://www.mmc.or.jp/ (Thin Film Testing Methods, MMC TR(S001)).

The Micromachine Center is also responsible for some information exchange efforts, including conferences (the Micromachine Summit and the International Micromachine Symposium) and the elementary school Micromachine Picture contest that is intended to develop awareness among the younger generation about the importance of this technology.

There is a society for MEMS in Japan as well. The IEE Sub-Society on Sensors and Micromachines has 1500 Members, 400-500 of whom attend an annual symposium sponsored by the society. Membership is not restricted to Japanese. There are some non-Japanese members (mainly Koreans), and 60% of the papers are in English.

Several universities are developing MEMS coursework (including Waseda, the University of Tokyo, and Tohoku University). This includes both undergraduate and graduate courses on MEMS.

Finally, MEMS/micromachining museums exist at two locations, in Tokyo and at Tohoku University.

CONCLUSIONS

The Japanese have done a very good job at promoting the field through primary and secondary school education programs and museums. Both the Micromachine Center and the IEE have organized MEMS/micromachining conferences in Japan. Moreover, academic institutes are developing MEMS undergraduate and graduate level courses and are training industry personnel as well as students.

As has been described, the Japanese have a wider view of processes and technologies, probably because of their mechanical engineering roots in MEMS and micromachining. Because of this wider view, the Japanese researchers are more willing to use milli-machining and rapid prototyping methods than their U.S. counterparts. However, several researchers visited recognized the need to drive standards in this industry. worldwide. There are too few standards, so the cost of production for MEMS/micromachined devices has been negatively affected. Furthermore, in Japan, a "build and test" approach exists in the design of MEMS/micromachined devices, and there is very little exposure to MEMS packaging, test, and reliability.

Foundries are beginning to emerge in Japan. The typical goal is to augment production demand in existing facilities. Both Omron and Olympus cited this during our visit. Other companies and universities, including: Sumitomo, Dai-Nippon Screen Printing, Sony USA—San Antonio, and Ritsumeikan, are also now offering foundry services. The coordination of foundries (i.e., similar to the MEMS Exchange) has not yet developed but is being pursued by the former Mechanical Engineering Labs (now, ISEMI) in Japan.

The Japanese have also developed several international collaborations, especially with Asian and European groups. During the visit, we did not encounter any American researchers in the Japanese labs. Our belief is that this could be beneficial, as it would provide an American a broader view of the technology, as well as language and cultural training.

A clear future trend for Japanese MEMS/micromachining is toward the MicroTAS/Microfluidics application. We encountered several groups tailoring their research to this field and heard several times that the next government initiative in MEMS would likely be in this area.

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CHAPTER 5

MEMS IN JAPAN: INDUSTRY PERSPECTIVES

Andrew A. Berlin

MEMS industry activities in Japan are evolving rapidly in ways that will change their character substantially over the next five years. For the past 5-10 years, the bulk of MEMS activity in Japan has centered on the development of inertial sensors, as well as on the use of MEMS sensors and actuators for catheter-like devices for biomedical applications and for industrial inspection applications. Examples of these products include accelerometers for automotive applications and proximity sensors and micro-welding devices for catheter tips. In pursuit of these applications, Japan has developed strong micromachine design capabilities and world-class facilities for fabricating MEMS devices, both in industry and in academia.

Today, the MEMS industry in Japan is seeking to bring its capabilities to bear on new markets and is undergoing three fundamental changes as a consequence of this pursuit. First and most notable among these changes, the technology focus is shifting away from catheters and towards microfluidics for biomedical, chemical synthesis, and fuel cell applications. In contrast to the relatively small size of the catheter market, each of these new directions can potentially become a relatively large and lucrative market. A second major change is that several industry-based MEMS fabrication services have been created in the latter half of 2001, making access to MEMS more widely available. A university-based fabrication network is also under development. The third major change is that Japan is nurturing a nascent entrepreneurial, small company venture-based model of technology development that is in the early stages of creating new relationships between industry and academia.

ENTREPRENEURIAL ENVIRONMENT

The Status Quo

To understand the environment that has historically faced MEMS startups in Japan, it is worthwhile to consider the case of a small MEMS company called Wacoh. Founded in 1988 by Mr. Kazuhiro Okada, for many years Wacoh was in essence the *only* MEMS startup company in Japan. This is in stark contrast to a point in early 2000 at the height of the optical MEMS boom, when there were several hundred MEMS startup companies in the United States. Wacoh is a fabless MEMS design company with a strong intellectual property portfolio. Wacoh's product line focuses on inertial MEMS, producing products such as accelerometers and gyroscopes. It has several major customers such as Sony, which uses a Wacoh gyroscope sensor in its robotic dog Aibo. The company has also developed a MEMS shear stress sensor, intended for use as a thumb-driven pointing device for cellular telephones, converting pressure exerted by a finger into smooth mouse-like functionality for phone-based video games, on-screen navigation, and web surfing.

Wacoh, with its unconventional small-company style of commercializing products, has become somewhat of a celebrated case in Japan, with articles about its founder appearing in the popular press. The company has developed a network of approximately 20 suppliers that fabricate and package its devices. Wacoh is pioneer for the concept of a fabless MEMS company, having developed its network of fabrication suppliers long before any of the major companies in Japan were offering organized MEMS fabrication services. To establish Wacoh, its founder Mr. Okada worked for eight years in isolation, writing over 100 patents and doing hands-on design work himself, prior to either hiring a staff or initiating outsourced product development. This led to a strong patent position that established credibility and enabled Wacoh to join with larger companies to form a fabrication network. As organized industrial fabrication services in Japan are now beginning to emerge, the barriers to creating MEMS companies using this business model should be substantially lower than those Wacoh faced 10 years ago.

The environment faced by Wacoh is tremendously different from the startup environment in the United States during this period. As illustrated in the tables below, the United States has extremely active startup activity, both in terms of venture funding levels and in terms of merger and acquisition activity. Recently the number of MEMS startups in the United States has been gradually declining, as we leave an era of abnormally high activity, spurred in part by Nortel's $3.25 billion acquisition of the optical component company XROS in 2000. Yet even with this decline, the activity level in the United States remains high relative to Japan, with 50-100 startups active in the MEMS technology area at the present time.

The WTEC panel had an interesting discussion with Mr. Okada about the reasons MEMS startups are more common in the United States than in Japan. He showed us the chart reproduced below in Table 5.1 and went on to explain that the key difference lies in how creation and subsequent failure of a venture is viewed by society. In the United States, having been involved in a startup, or even multiple startups, is viewed as valuable experience, even if in the end the startups failed. In contrast, in Japan being involved in a failed venture is viewed as a personal failure, with substantial disgrace associated with it. Due to the dominant method for funding new ventures in Japan, which requires substantial contribution by the founders, failure of a small business venture typically also leads to personal bankruptcy of the founders, along with the stigma and long-lasting personal complications that bankruptcy entails. After being involved in a failed venture, one is not considered desirable or 'experienced.' Rather, it becomes virtually impossible to start a new venture, and it is challenging to obtain a salaried position. Mr. Okada made it clear that he views the consequences of the failure of his company as in essence being exiled from mainstream society.

Table 5.1
Select mergers and acquisitions of companies pursuing MEMS technology development in the United States during January-September 2001

MEMS Company	Acquired By
Advanced MicroMachines	BF Goodrich
XROS	Nortel
Cronos	JDS Uniphase
Intellisense	Corning
Clinical Micro Sensors	Motorola
Silicon Light Machines	Cypress Semiconductor
BCO	Analog Devices
Kionix	Calient
Total Micro Products	Kymata

This high personal cost of failure is compounded by the unavailability of venture funds in Japan. Unlike in the United States, where a business may operate for three to seven years before becoming profitable, sustained by venture funding, in Japan a new venture must become profitable very quickly if it is to survive. Wacoh has been profitable since the day it was founded, primarily by keeping employee numbers small and by supporting itself via outside consulting. This slows the development of the new business and increases the role that patent protection plays in creating value. Indeed, most of the business development activity of Wacoh for the first five years took the form of patent filings, funded by consulting revenue.

Table 5.2
Select private equity investments in companies pursuing MEMS technology development in the United States during January-September 2001

Company	Field of Interest
HandyLab	Biological
Lumicyte	Biological
Microlab	Biological
Micronics	Biological
Molecular Reflections	Biological
Fluidigm (fka Mycometrix)	Biological
Nanostream	Biological
Verimetra	Biological
Ion Optics	Chemical Sensors
MEMSIC	Inertial Sensors
Advanced MicroSensors	Infrastructure
Colibrys	Infrastructure
Coventor (fka Microcosm)	Infrastructure
Cronos	Infrastructure
Integrated Sensing Systems	Infrastructure
MEMSCAP	Infrastructure
PHS MEMS	Infrastructure
Standard MEMS	Infrastructure
Tronics Microsystems	Infrastructure
Advanced Integrated Photonics	Optical
Agility	Optical
AXSUN	Optical
C Speed	Optical
Calient	Optical
InLight Communications	Optical
Integrated Micromachines	Optical
Iolon	Optical
LightConnect	Optical
MEMS Optical	Optical
Ondax	Optical
Onix	Optical
Optical Micro Machines (OMM)	Optical
Transparent Optical	Optical
Umachines	Optical
Xros	Optical
Crossbow	Sensornets

Table 5.3
Chart showed by Okada-san to illustrate the differences between the United States and Japan in attitudes towards new ventures

	Japan	United States
Fund Procurement	Challenges • Financing (principal) • Investment (secondary) • No informal investor (problem in terms of tax laws)	Easiness • Investment (principal)
Social / Business environment	Bad • A track record is more important than performance	Good • Performance is important
Failures	• Lose all possessions • Impossible to form company again	• Only time left to lose • Evaluated to be successfully debugged

Looking forward

Japan is taking measures to encourage a greater rate of formation of startup businesses. Various efforts are currently underway to reform bankruptcy laws. As recently as 1999 a new form of corporate bankruptcy was created in Japan that permits gradual restructuring of a business while providing protection from creditors, a form of bankruptcy protection that has been commonplace in the United States for many years. Mr. Okada indicated that further changes are needed if Japan is to encourage widespread formation of startup businesses, particularly with regard to certain tax laws, which make the formation and operation of venture capital funds difficult.

Within the past two years, early signs of MEMS venture initiation have been appearing. For instance, Professor Esashi at Tohoku University has formed the ‘New Business Creation and Hatchery Center’ and has brought people into the university whose goal is to start small MEMS companies based on the results of their work in the university microsystems lab. Prof. Kitamori at the Kanagawa Academy of Science and Technology also has people in his lab who plan to start small companies. Prof. Sugiyama from Ritsumeikan University has already formed a small company to coordinate foundry services among various MEMS fabrication facilities.

Virtually every university that we visited had formed a technology licensing office within the past two years. The faculty we met with viewed this as a necessary and important step. However, they indicated that the licensing operations are new and that the model for how they will work is still being figured out. Licensing of university intellectual property (IP) in Japan is complicated by the fact that for the most part the university does not own the IP produced in its laboratories. Graduate students and postdocs are funded through a variety of educational funding programs, independent of the university research funding, and in most cases personally own the IP they produce. Although a few government funding programs do require that IP be assigned to the government, these are the exception rather than the rule, and even in these cases control of the IP does not rest with the university. Thus in most cases the university is at best a co-owner of the IP, making the role of a licensing office somewhat difficult to carve out. The universities are beginning to experiment with various models of IP ownership, and this is an area that is likely to continue to evolve over the next five years as Japan seeks to put in place the mechanisms required to support small business incubation.

Finally, international exchange of researchers is gradually changing the culture of MEMS research in Japan. In labs that include exchange programs, more students tend to work in areas that resemble the focus areas of United States and Europe, such as optical MEMS, than is the case in labs that do not include significant international activities. The impact of the international exchange extends beyond the selection of technical topics, exposing students in Japan to alternative ways of thinking about issues such as markets, intellectual property, new business incubation, and so forth.

For example, at the Center for International Research on MicroMechatronics organized by Professor Fujita at the University of Tokyo, students receive degrees from CNRS in France based on the work done while visiting Japan, while students from Japan receive degrees from the University of Tokyo based on work done in France. Additionally, industrial researchers from Europe and the United States visit the laboratories in Tokyo for two to three years at a time. To illustrate the impact that international exchange has on project selection, Professor Fujita showed us a chart, pictured below in Figure 5.1, that emerged from a conversation with an industrial collaborator from the United States. The chart delineates the boundary between 'winner' and 'loser' applications. Professor Fujita further explained that he views MEMS foundry services as changing the slope of the win/lose boundary line, in essence making it possible to practice MEMS without having to build up a proprietary fabrication capability. Thus, the initial investment and risk are lowered, enabling MEMS to profitably address smaller markets and to be more competitive with alternative technologies.

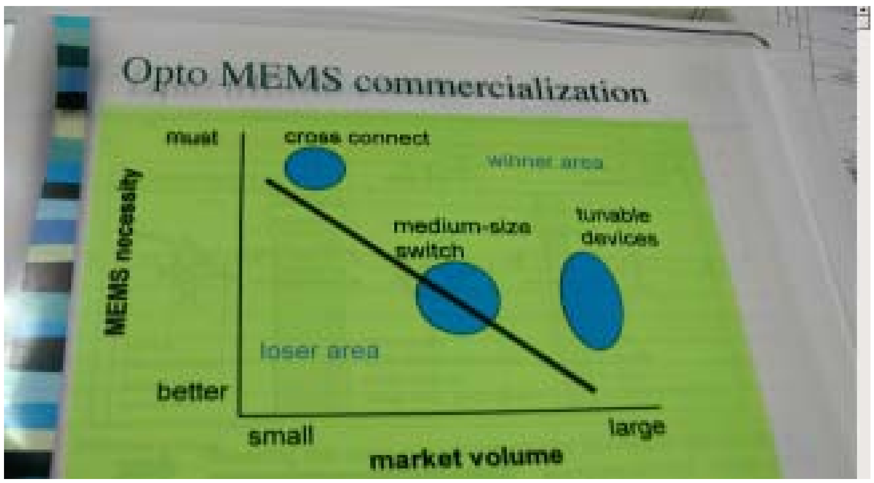

Figure 5.1. Tradeoffs in optical MEMS commercialization. The vertical axis reflects the degree to which MEMS is the only technology available to meet a particular need, while the horizontal axis reflects potential market volume. Professor Fujita used this chart to illustrate the influence that industrial and international collaborations have had on university project selection.

MEMS FOUNDRY BUSINESSES AND BUSINESS MODELS

Within the past year, five major companies have announced the formation of businesses to provide MEMS foundry services: Omron, Olympus, Sumitomo heavy metals, Yokogawa, and Dai-Nippon. The emergence of these new business services is inspired in part by excess semiconductor fabrication capacity, primarily relatively old 4-inch silicon wafer processing lines. While these lines represent fairly old technology for electronics, for MEMS applications, which typically involve much larger feature sizes, they can serve as high quality fabrication facilities. Thus MEMS is seen in part as a way to extract added revenue from this existing, fully depreciated infrastructure.

From a business perspective, the MEMS fabrication industry in Japan appears to face two serious challenges. First, each fabrication service appears to be attempting to operate independently using a proprietary process model, rather than moving to the sort of cross-foundry standardization that made CMOS successful or towards creating a network of compatible suppliers that would encourage the formation of additional fabless MEMS design houses, along the lines of Wacoh. In academia there is not yet an organized multi-site fabrication network in Japan, akin to the role of the MEMS Exchange in the United States. However, there are various informal networks, consisting of faculty members networking with their personal contacts in industry to put together MEMS fab runs on an as-needed basis. Formalizing these relationships and establishing standards is a next step that several faculty members indicated Japan's newly emerging MEMS fabrication industry must address.

A second major challenge facing the MEMS fabrication industry in Japan is that the companies that are offering fabrication services often have business models that are somewhat conflicted. For example, at one newly-opened MEMS foundry service we visited, the management stated, "We intend to be the primary *fabricator* of MEMS components in the world." Yet this company is also a primary *designer* of MEMS components, in essence competing directly with the companies it would like to attract as customers. As one executive of the company said, this is like "shaking your hand and punching you in the nose at the same time." Although the business model has been successful in some areas of the electronics industry, becoming the primary supplier in the world while using the profits from that endeavor to compete with one's customers is an inherently unstable situation. So looking forward, one possible evolution of this industry will be that foundry services may find it desirable to split off from their parent companies and either merge with one another or agree on standards that permit them to form a supplier network to create a powerful MEMS fabrication industry in Japan.

INDUSTRY/ACADEMIA RELATIONSHIPS

Another key difference between the United States and Japan is the relationship between universities and companies. In the United States, one of the roles that small startup companies play is to couple university laboratory research to large company product development. In a typical scenario, a university professor and graduate student will invent a technology in a university lab and then form a company to further develop that technology and bring it to the point where commercialization and product development can really begin. Shortly after that, a larger company will often become involved, either through direct acquisition of the small startup or through a collaborative producer/supplier relationship. In the U.S. biotechnology field, it has become typical for a small company to have a plan for getting to market that involves being acquired by a larger firm. Although in the electronics field this is a somewhat more unusual business model, in MEMS and especially in the area of optical MEMS, being purchased by one of the four or five major optical equipment suppliers has become a commonplace strategy. Thus in the United States, in part the startup community acts as a buffer between nascent technologies and mainstream product development.

In Japan, this technology buffer of startup companies does not exist. In contrast, major companies engage with universities much more directly. Indeed, it is common for company researchers to outnumber graduate students *in university labs*. It is also common for university labs to be working on an item which will be directly transformed into a product. Professor Esashi's lab is a nice example of this. At any given time, there are 20-30 industry collaborators working in his microsystems lab. Current industrial collaborators include Akebono, Fuji Film, Anelva, Tokyo Elect., Hitachi C., Advantest, Sony, Canon, Myotoku, Advantest, Taiwan ITRI, Chemitronics, Moritex, and Vietnum.

Figure 5.2. Examples of products that have emerged from work done in Professor Esashi's lab. Left: pH sensor for fish tanks, where pH is used as an ammonia sensor. Right: Biosensor that detects pyroli bacteria based on immobilized enzyme assay.

With a spirit of technology co-development that is rare in U.S. universities, Professor Esashi proudly maintains a catalogue of dozens of products that have emerged from his laboratory, such as the pH sensor for fish tanks and the biosensor pictured above in Figure 5.2. Despite this deep corporate involvement in his laboratory, it is important to note that Professor Esashi maintains an open research environment—all see what the others are working on. Companies are expected to file sufficient patents to protect their products prior to engaging the lab in research and prototyping activities. Any further intellectual property developed at the university lab is shared between the company and the university. This open environment, combined with the wide variety of activity, creates a MEMS educational environment on a par with the best found anywhere in the world.

SELECTED TECHNOLOGY FOCUS AREAS

Inertial and Automotive MEMS

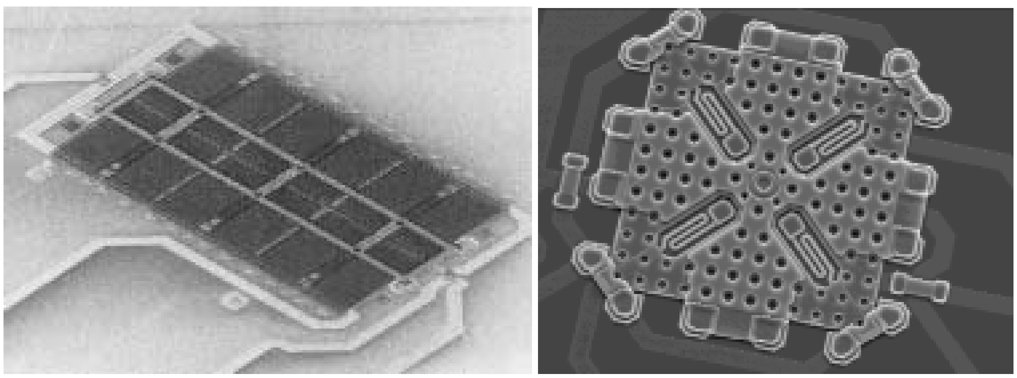

Figure 5.3. Motorola 'g-cell' accelerometer platforms to be manufactured in Sendai. Left: lateral (x-axis) accelerometer. Right: Z-axis (folded beam) accelerometer.

MEMS sensors for automotive applications are being developed in Japan at Toyota Central Research Labs, Motorola, Omron, and numerous other companies.

In late 2001, Motorola announced that it will convert one of its fabrication facilities in Sendai into a MEMS processing line, primarily for automotive applications. This includes fabrication in Japan of Motorola's 'g-cell' platform accelerometer system (Figure 5.3, above), as well as fabrication of MEMS tire pressure sensors. The tread act in the United States requires remote monitoring of vehicle tire pressure in every new car sold in the United States beginning in 2003. With five tires per automobile and several hundred million automobiles sold per year, this represents a major market opportunity for MEMS-based wireless pressure sensors. A MEMS pressure sensor will be combined with the wireless chip set currently used in automobile key-chain remote controls to produce an insert that resides on the interior portion of the tire stem. A wireless receiver mounted on the dashboard will be used to monitor tire pressure every few seconds.

When the previous WTEC report was written in 1993, Toyota Central Research Labs was one of the most active MEMS research establishments in Japan. Today, as MEMS automotive components have become readily available commercially, the labs have shifted their emphasis to alternative sensing methodologies, focusing on three main areas. These three areas are *environmental* sensors (to monitor and/or reduce pollution); *safety systems*—novel types of inertial sensors; and *information and communications*, such as development of a millimeter scanning radar for object and lane detection. In the MEMS area, research activity is primarily in the areas of vibrating gyroscope design, the development of methods for the tensile testing of thin-films, and methods for reducing vertical stiction in MEMS devices.

Optical

There is a moderate level of activity on optical MEMS in Japan, centered at companies such as Olympus and Sony. This activity is generally focused on the application areas of instrumentation, catheters, and displays.

In contrast to the United States, there is little work on MEMS for optical communication. We are aware of only one optical communication project in Japan, an optical switch being developed at Professor Fujita's laboratory at the University of Tokyo. This is in part because with only one dominant bandwidth provider in Japan (NTT), there has not been a tremendous 'gold rush' to acquire MEMS optical switching capability before competing bandwidth providers are able to do so. Another reason for this differing emphasis is that the Micromachine Project, through its funding and its effect on the culture (what is deemed important to work on), heavily emphasized catheter applications and consequently optics such as micro scanning mirrors that can be placed on the end of a catheter. Sony has some MEMS display activities under way, while Professor Fujita's lab has projects underway in the area of MEMS-based tuneable lasers, optical switch elements, and a 2-D optical scanner.

bio-MEMS

For the past several years, catheters have been the focus area of bio-MEMS activity in Japan. Almost every research lab that we visited had a catheter somewhere. Olympus in particular stood out, having a large showcase room filled with catheters and various cleverly designed MEMS components that could be mounted on them. As illustrated in Figures 5.4 and 5.5, MEMS in catheters play roles ranging from position sensing and actuation to proximity sensing (how close the tip of the catheter is to a wall) to micro-tweezers and welding devices. Few products have resulted from this effort, although some appear to be in the pipeline towards commercialization at Olympus.

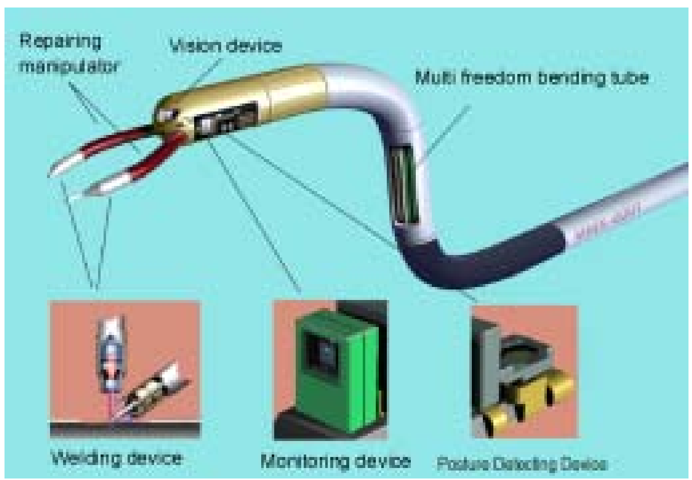

Figure 5.4. Schematic diagram of MEMS devices mounted on catheters and pipe repair instruments.

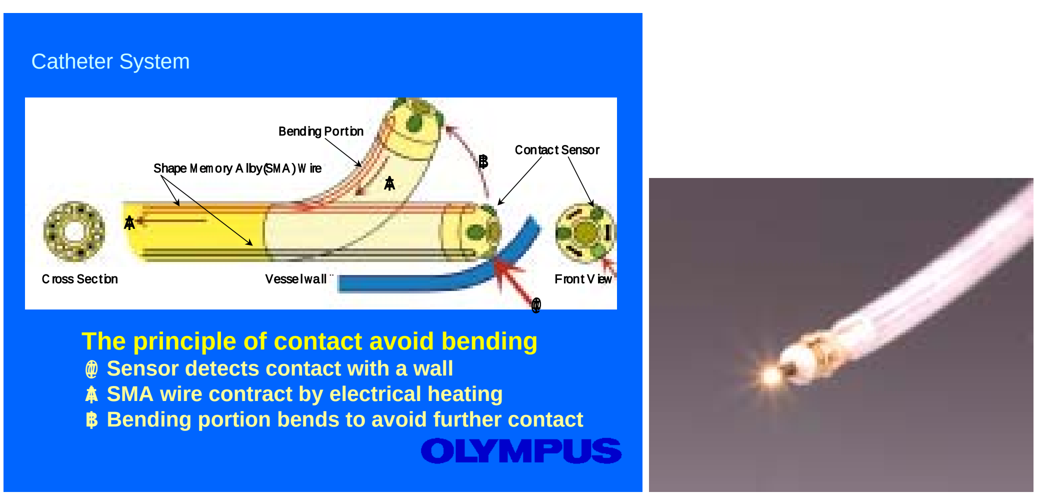

Figure 5.5. Olympus microfine active bending catheter equipped with contact sensors.

Today, the focus of bio-MEMS activity in Japan has largely shifted towards microfluidics and on-chip analysis. Professor Shoji at Waseda University has an interesting project on soft lithography-based microfluidics, in which a building-block approach is used to create semi-custom fluidic component arrays on a chip. An antibody-based assay is being incorporated into the channels as well. A novel valve design, in which a laser is used to trigger gelation within a channel, has been experimentally demonstrated. Within industry, Olympus and others are aggressively pursuing business plans related to DNA probe arrays, although no products have yet been announced. Hitachi has also announced that it has formed a bio-MEMS group. The microfluidic and DNA analysis efforts in Japan are at the research stage and are relatively new in comparison to efforts in the United States, where the total sales of biochips is now on the order of $300 million annually. However, in other areas such as ion-sensitive transistor-based sensors, Japan has had products for many years.

Nanotechnology

Everywhere we went, we saw MEMS groups beginning to focus on nanotechnology. In one sense, MEMS can serve as the interface between the macro-scale world and the nano-scale world. In another sense, as dimensions continue to shrink, different types of MEMS devices become possible on the nanometer size scale than were possible at the micrometer size scale. This is clearly going to be a focus area for Japan over the next few years. Potential industrial applications we heard about include data storage, biosensing, and on-chip chemical synthesis. Activities in nanotechnology are covered in a separate WTEC report (reference goes here).

SUMMARY, CONCLUSIONS, AND PREDICTIONS

Technology and Market Focus

Japan has developed world-class technical know-how, fabrication facilities, and educational institutions that enable the practice of MEMS technology. Although during its formative stages over the past few years much of this activity has been technology-driven rather than market-driven, leading to relatively few commercialized MEMS products, there is little reason to expect this lack of market-focus to continue. Today, the technological pursuit of nanotechnology and microfluidics has largely replaced the pursuit of catheters. This pursuit brings with it an emerging focus on new markets, particularly in the areas of bio-MEMS, chemical synthesis on a chip, and fuel cells.

Fabrication businesses

Organized MEMS fabrication service businesses in Japan are brand-new and still in the process of being organized and defined. The goal is clearly to be the primary MEMS manufacturers in the world. While this may sound unlikely at first, given the many fabrication services already available in other parts of the world; in fact it is plausible that Japan could succeed. Although the United States has many foundries, it lacks quality standards. The lack of standards in turn makes it difficult for foundries to interoperate with one another. Further, the business model at many U.S. foundries is “send us your design, we’ll run it through our equipment and send you chips back.” There is rarely a guarantee that the equipment will produce a specific result or implement a specific, sustainable fabrication process that one could base a serious productization effort on. Basic assurances—that the parts built next month will have similar characteristics to the ones built this month or that the parts will match a simulation model—are quite difficult to obtain. As a consequence, each major MEMS product currently has a fabrication line directly associated with it.

In Japanese MEMS research, characterization and reliability of devices appear to be given substantially more attention than in the United States, probably as a consequence of the high level of industry involvement in MEMS research activities. At Waseda University, for instance, the floor space devoted to characterization equipment likely exceeds the floor space devoted to fabrication equipment, with about one dozen characterization techniques available, ranging from NMR to SEM. This emphasis on characterization is quite different from the focus in the United States. If this characterization capability is able to be moved over to the fabrication businesses in a way that permits Japanese MEMS foundries to offer services that meet meaningful quality, reliability, and interoperability standards, Japan may indeed become the vendor of choice for MEMS fabrication.

Industry / Academia Relationships

With technology licensing offices just forming and extensive visitor programs being implemented, the rate of formation of startup businesses is expected to grow. This is still a nascent activity in comparison to the United States and Europe, but there is a clear commitment to grow a venture-based MEMS industry. This growth will be further accelerated if new fabrication businesses are successful in lowering the barriers to operating fab-less MEMS design businesses.

Conclusion

In conclusion, it is important to note that the rate of change of both academic and industrial MEMS in Japan is very high—this is a time of transition. Figure 5.6 shows a photograph of a building that was under construction during the time of the WTEC panel's visit to Japan. In contrast to the United States, where one or perhaps two cranes might be used to erect a building, construction in Japan apparently takes quite a different approach. In the three hours that we were in our meeting, one of these buildings went from a mostly vacant concrete frame to having completed walls on several floors. The bottom line message of our report is that there is tremendous expertise and world-class facilities to do MEMS in Japan. There are also substantial efforts underway to transform both the technical directions and the business environment surrounding MEMS in Japan. Just as in building construction, be prepared for things to be done a bit differently—and possibly to progress far more quickly than one might expect.

Figure 5.6. Multiple-crane method of building construction in Japan.

CHAPTER 6

MICROSYSTEMS TECHNOLOGIES IN JAPAN

Mark G. Allen[1]

INTRODUCTION

This chapter is divided into several sections. In the first section, some definitions of microsystems technologies from both the Japanese and the U.S. perspective are examined, both historically as well as current day. In the second section, specific examples of current fabrication technologies and devices achievable using those technologies are specified. Finally, overall conclusions and recommendations are drawn from the microsystems technologies observed.

What are Microsystems Technologies – the Definitional Problem

It is very difficult to discuss 'Microsystems Technologies in Japan' without first precisely defining terms. In the United States, the term 'microsystems' has grown out of MEMS, which in turn grew from micromachining, the use of integrated-circuit-related fabrication technologies to create mechanical structures in silicon and other materials, potentially in addition to electronic devices. This *manufacturing-related* definition has persisted throughout the United States, and micromachining, or more recently MEMS, has been defined as 'a way of making things' rather than structures of a particular geometry or size range.

In Japan, a very different view of MEMS grew, perhaps due to the influence of the MITI project of the early 1990s (described below), as well as to building upon core Japanese industrial strengths and to the desire to open new fields of research not being exploited by U.S. researchers of the time. The Japanese approach, perhaps more precisely termed 'micromechatronics,' was exemplified by many Japanese submissions to the IEEE MEMS meetings of the period, in which precision machining and utilizing 'big machines' to make 'small things' was quite common. Although difficult to generalize, it seems clear that much Japanese development in MEMS emphasized the device itself, rather than a manufacturing-related approach.

This interesting difference of opinion has led to some interpretive issues when defining whether, researchers in Japan, especially industry researchers, are performing what U.S. MEMS researchers are defining as MEMS. For example, in spite of the microfluidic elements present in one host company's systems, representatives of that company stated, "we don't do MEMS." Similarly, researchers at another Japanese company have stated that "[there are] no MEMS in our products," even though they offer products known to incorporate micromachined accelerometers. It should be emphasized that these are not failures to communicate or attempts to mislead, but that these statements arise solely from the definitional issues described above.

[1] With assistance of WTEC staff.

On the other hand, in general academic researchers in Japan tended to take a much broader view of MEMS and microsystems, more analogous to the U.S. definitions. More recently, these two viewpoints are coming together in the term 'microsystems,' and each country is recognizing the merits of (and incorporating some of the approaches of) the other in their current microsystems research.

Historical and Current Viewpoints

It is instructive to compare the relative viewpoints of both Japan and the United States 10 years ago (approximately the timeframe of the last report) and to compare that situation with today. Ten years ago, U.S.-based MEMS programs had their roots firmly in silicon and complimentary metal-oxide-semiconductor (CMOS) processing. Based on this infrastructure, the fabrication technology expanded to build lithographically-based microsystems. Although there were clear exceptions to this paradigm, like ion-beam fabrication and laser-assisted sequential etching technologies, by and large the batch-fabrication approach along with silicon integrated circuitry was utilized as the foundation for microsystems development. On the other hand, as discussed above, Japanese 'MEMS' clearly had its roots in mechatronics. Perhaps the classic example of this approach was the 'micro-car,' a *tour de force* of conventional precision machining, in which large machines were used to make tiny functional objects in a serial fashion, including (as a technology demonstrator) a microscopic metallic car with functional doors, hood, trunk, and wheels—and an electric motor.

The diverse viewpoints were reflected in the subsequent research directions of the two countries over the decade of the 1990s. The United States invested heavily in the development of lithographically-based fabrication technologies, in silicon as well as a variety of other materials. Japan invested heavily in the micromechatronics approach, exemplified by the MITI MTP project. In this project, several end applications for microsystems helped to define research vehicles for technology advancement. These end applications included telerobotics and catheter-based systems for investigation of the internal integrity of pipes for power plants; medical applications of catheter-based systems; and a 'microfactory' project for the rapid fabrication of small-scale parts. This device-based approach, with few to no constraints on the manufacturing approach, contrasted strongly with the U.S.-based manufacturing-approach definition of microsystems. Today, after a decade of research, both countries are recognizing the merits of the other's approaches. Significant investments in lithographic-based MEMS capability and equipment over the past few years were observed, as Japanese laboratories have sought to capitalize on the decade of advancement in lithographic-based MEMS.

Perhaps key insight into the current Japanese philosophy toward microsystem technology can be gleaned from the following comment from one of our hosts: "[A] system has its own size. Miniaturization is not always possible or necessary. But, for many key devices of the system, miniaturization can be very essential and important."

Facilities and Funding

In general, the visiting panel was struck by the great improvements in university facilities over the past 10 years. These improvements are clearly driven by the large investment of the Japanese government in universities. Due to the nature of government funding of universities in Japan, almost all of this funding was directed at facilitization. As described elsewhere, in Japan most discipline-specific funding of universities is directed at equipment. Student stipends and faculty salaries are covered in the base budget allocations to universities, unlike U.S. government-based research funding. Furthermore, there is an extensive presence of visiting engineers from industry in the university laboratories. The engineers are a valuable resource in the research and development of microsystems at the universities; and since their salaries and expenses are covered by their home companies, their presence allows further use of government funds on infrastructure research and development. At some laboratories, investments of greater than 90% of received government funds were utilized for infrastructure. This approach is very different from the U.S. approach, in which much government funding is directed away from equipment and infrastructure investment with the exception of certain targeted infrastructure development programs.

In addition to the concentration of government resources on equipment and infrastructure, funding is uneven from institution to institution. Some university facilities, such as the national universities and so-called ‘venture laboratories,’ received substantial benefit from this approach, while other facilities and universities have not benefited as much. The concentration of resources has led to the establishment of a few world-class concentrations of microsystems laboratory equipment in Japan. Several of the research projects that illustrate some of the Japanese approaches to microsystems over the past several years are illustrated in the next section. It should be emphasized that this review is not an exhaustive list, due to the time constraints of the WTEC visit as well as the vast number of technologies observed even during this limited visit. However, the technologies have been selected to give a flavor of the current state of the art of microsystems technologies in Japan.

REVIEW OF JAPANESE TECHNOLOGIES

Although it would be impractical to detail every fabrication technology in use in Japanese microsystems laboratories, highlights of some of the various approaches are given below. These illustrate not only some of the capabilities of the Japanese laboratories, but also some of the current thinking regarding the approaches to microsystems fabrication that are currently being undertaken.

Batch Assembly Processes (active catheter)

The original plan for the MITI Micromachine Project included a project for the development of a MEMS-based catheter device for medical applications (Wise et al. 1994, p. 111). This WTEC panel saw some results from the MITI-funded work, and some follow-on work as well.

In particular, Olympus, one of the original participants in the MITI program, has developed several different types of catheters and is exploring industrial applications of this technology, including field repair of damaged pipes. A laser-welding catheter that can weld cracks in pipes in-situ has been developed. The laser used is a YAG laser and provides a power of over 70 W over a 0.5 mm depth. Pneumatic actuators are used to actuate the tip of the catheter as it is inserted into the pipe of interest. Murata has developed a gyroscope-based MEMS position sensor for the original MITI catheter project, which it has continued to develop and has targeted towards automotive applications. See site reports in Appendix B for details of the work at Olympus and Murata.

Prof. Esashi of Tohoku University lists active catheter-based maintenance systems for extending the life of machinery as one of the principal topics for research in his laboratory. Also at Tohoku University, shape-memory actuators (coil and spring) have been used to make a steerable catheter with a 0.5 mm outer diameter. Dr. Yoichi Haga, a medical doctor working as a research associate in this laboratory, is launching a spin-off company to commercialize the active catheter.

This WTEC panel saw a large, diverse range of research projects being performed in Japan using catheters as a unifying example. In general the panel observed batch assembly processes frequently. The Japanese (and we will see this again in other examples below) do not seem to be afraid of the concept of non-integrated MEMS, of assembling components to form a system.

Selective Laser Ablation

Selective laser ablation is one of the technologies that this panel observed under development for MEMS device fabrication in Japan. Laser patterning, especially excimer laser ablation of aromatic polymers such as polyimide, was used to fabricate a variety of biomimetic structures. This approach has led to structures that include the swimming and flying microactuators shown in Figures 6.1 and 6.2, from Prof. Esashi’s laboratory at Tohoku University. The flying and swimming microactuators consist of a polyimide ‘tail’ or ‘bridge’ that connects the magnetically permeable ‘wings’ or ‘head’. By placing the microactuator within an oscillating magnetic field, the actuator can be induced to swim or fly.

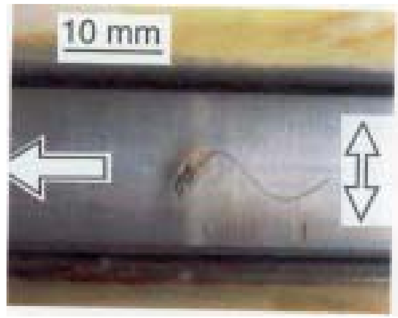

Figure 6.1. A fin-type swimming microactuator composed of a small magnet with a polyimide film (Esashi Laboratory, Tohoku University).

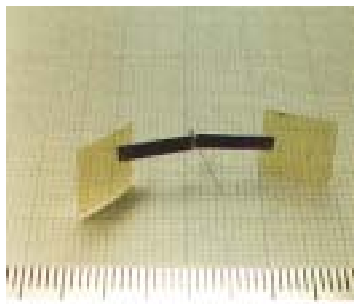

Figure 6.2. Flying microactuator with two magnetic wings attached to the body of a soft magnetic wire (Tohoku University).

Projection Exposure for Non-Planar Lithography

Projection lithography for non-planar surfaces was demonstrated, not only for spherical surfaces such as that utilized by Ball Semiconductor in its spherical MEMS devices, but also for cylindrical surfaces such as the tips of catheter devices. One non-planar lithography technology that was discussed was being exploited in the fabrication of suspended, spherical-proof-mass, multiaxis accelerometers. Prof. Esashi's laboratory at Tohoku University is working with Ball Semiconductor in the United States and with Tokimec, a Japanese manufacturer of navigation-grade gyroscopes, to develop a 1 mm diameter silicon ball for inertial sensing. A polysilicon sacrificial layer is removed in a novel way: XeF_2 permeates a porous ceramic coating to free the ball. Electrodes patterned around the ball are used to levitate it, with the electrostatic forces required to maintain a stable position reflecting the inertial forces on the ball.

Projection exposure for non-planar lithography was also demonstrated using X-ray approaches at Ritsumiekan University. This was utilized in the direct micromachining of polytetrafluoroethylene and is described in the LIGA subsection below.

Piezo and Pyroelectric Film Deposition (sensing and actuation)

As an example of the combination of 'traditional' MEMS fabrication technologies with new materials, Professor Okuyama's laboratory at Osaka University is experimenting with the development of infrared image sensors using barium strontium titanate (BST) as a bolometric material. The approach was to determine the change in the dielectric constant of the BST due to temperature fluctuations caused by exposure to infrared radiation. A silicon substrate is etched to form thermally isolated structures. The technology approach is wet etching of (110) silicon. Pt/Ti is used as a CMOS metallization, followed by BST deposition and an infrared-absorbing material on top. The Pt/Ti metallization is required since the film deposition temperatures are typically high (on the order of 400-600 C). The device has a sensitivity of 1.2 kV/W and a detectivity (D*) of nearly 3×10^8 cm $(Hz)^{0.5}$/W. (See site report in Appendix B for details.) Olympus is offering thin film deposition and electroplating as part of its MEMS foundry service.

High Temperature Materials for Power MEMS

Other nontraditional materials for high temperature and power MEMS are also being investigated. For example, silicon carbide and silicon nitride micromachining for microturbine applications is being researched at Tohoku University under the direction of Prof. Shuji Tanaka (Fig. 6.3). Since silicon carbides and nitrides are such inert materials (thus their desirability in aggressive environmental applications), forming fine features many tens or even hundreds of microns in thickness is very difficult. Prof. Tanaka is therefore leading a two-pronged approach: the first is to use conventional machining techniques to create the desired structures; the second is to utilize microsintering into 'traditionally-micromachined' (e.g., lithographically-defined and ICP-etched silicon) molds to create the desired microstructures.

Figure 6.3. Micro air turbine capable of 10,000 rpm. The prototype rotor is 5 mm in diameter and fabricated from SiN ceramics by nitridation of silicon powder (Esashi Lab, Tohoku University).

Microfluidics: Straightforward MEMS Technology with Sophisticated Chemistry

Several research groups in Japan are focusing on microfluidics as a key application area for MEMS, with significant activity underway at Olympus, Shimazu, Sony, Tohoku University, Waseda University, and Kanagawa Academy of Science and Technology (KAST). Professor Kitamori's group at KAST is among the more active university-based groups in this arena. His approach is to use standard microfabrication techniques to form microfluidic platforms, in which he does highly sophisticated, innovative chemistry. A major goal of this research is to extend the domain of integrated chemistry beyond the limitations of state-of-the-art capillary electrophoresis-based approaches, which are limited to aqueous solutions, ionic species, and fluorescence-based detection. The substrate of choice is glass, with vertically stacked, interconnected chips being used for increasing the number of inputs and outputs. Much of his work is based on flow in channels that are 10-200 microns in diameter. However, his group is interested in the possibilities of "nanocapillaries" in which the behavior of water is unconventional. He hypothesizes that the capillary walls constrain the water clusters, resulting in different chemical behavior—such as a much longer decay constant for fluorescence. These capillaries are filled from the microchannels by surface tension. In order to connect the microflow chips to conventional microtubing, very small, precisely machined reusable plastic connectors are used. Recently Prof. Kitamori founded a small startup company co-located with KAST to market the microfluidic chip technology he has developed.

Prof. Shuichi Shoji at Waseda University is also working in microfluidics, using polymer, silicon, Teflon, and glass substrates. Teflon, which is somewhat unusual in MEMS applications, is deposited via spin-coating by Asahi Glass Company (the brand name is 'Cytop membrane').

Microfluidics and integrated chemistry will be the focus of a major METI program that will start in 2002. Another potential initiative is in microfluidic systems for cell-based biochemistry, which could be the focus of a Ministry of Agriculture program starting in 2003.

SAW Devices

Surface acoustic wave devices were exploited in a number of ways. Although much of the fabrication technology being performed was ‘straightforward,’ e.g., the lithographic-based fabrication of interdigitated electrodes on planar, bulk lithium niobate substrates, the applications of interest were novel. For example, in Prof. Shigeru Ando’s laboratory at the University of Tokyo, such devices were being exploited as haptic devices for robotic interfaces, in which the perceived ‘smoothness’ of the surface was electronically alterable by adjustment of the amplitude of the acoustic wave propagating between the interdigitated electrodes (Fig. 6.4). These technologies are also being pursued actively within the United States.

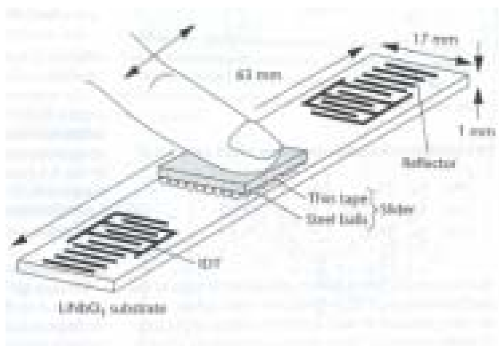

Figure 6.4. SAW devices: interdigitated electrodes on lithium niobate (University of Tokyo).

Advanced Electronic Bulk Ceramics

The WTEC panel observed some Japanese work on ceramics, including ceramics with interesting electrical properties, high dielectric constants, piezoelectrics, ceramic antennas, and sensors. Figure 6.5 shows some examples of piezoelectric and pyroelectric devices currently manufactured by Murata.

Figure 6.5. Murata ceramic-based products.

Although Murata’s MEMS work has been emphasizing the gyroscopes that were developed as part of the MITI project (see above), Murata representatives did express interest in RF MEMS. They felt that their expertise was in ceramics, and therefore, they were motivated to use ceramics to do what some researchers in the United States are doing with, e.g., micromechanical switches and relays. In addition, they see opportunities for high-dielectric-constant micromachined ceramic antennas as operating frequency ranges increase, and consequently, wavelengths decrease to on the order of the size of their parts. Murata plans to apply the RF MEMS concepts to 5 GHz cell phones.

Some of the Murata researchers stated a very intriguing philosophy. Perhaps influenced by their very successful components and parts business, they felt they had a potentially strong opportunity in the manufacture of 'MEMS components,' whereas many of the other industries that we visited were working more on 'MEMS systems'. Further, they felt that the opportunity for the hybrid assembly of MEMS parts could follow the successful manufacturing paradigm of pick-and-place hybrid assembly of complex systems that has been used for cellular telephones. This was exemplified by a (paraphrased) comment from one of our hosts: we are a components company and should play to our strengths.

Another ceramic development the panel observed in Japan is an ultrasonic signal-emitting device, developed under Micromachine Center funding, that uses high aspect ratio MEMS-like technology in ceramic. The device is being commercialized by Sumitomo Electric.

Wet and Dry Etching of Silicon

In addition to the work at Osaka University (mentioned above), the panel observed wet etching of silicon v-groove technology for alignment at Murata, Olympus, Tohoku University, and Hitachi. This is quite mature technology that is now being deployed in products. The panel heard a presentation at Hitachi's Mechanical Engineering Research Laboratory (MERL) on MERL's efforts in optical devices. The technology is based on V-grooves anisotropically wet etched in silicon followed by installation of optical fibers and ball lenses. Thin film metal solders are used to fasten the components together. These devices were introduced several years ago and are currently in production in another division within Hitachi.

Some silicon dry etching and deep reactive ion etching research is being done in Japan (e.g., at Murata, Tohoku University, AIST/ISEMI) and is offered as part of some of the foundry services (in particular at Olympus). This technology approach is also one that many U.S. researchers have been working on quite aggressively.

Glass Micromachining

Murata showed the panel an interesting packaging scheme using vertical through-holes sandblasted through anodically-bondable glass to both form a vacuum seal as well as electrical feedthroughs (Figure 6.6). A resilient organic mask is utilized during this process, and it takes 10-15 minutes to sandblast via holes through 500 microns of anodically-bondable Pyrex. The device is not integrated with electronics, and it has a packaged size smaller than 5 x 5 mm. The noise-equivalent angular rate is currently 0.3 degree/second in a 40 Hz bandwidth, and Murata is currently on its third or fourth generation device. These and other back-end processes are discussed further in Chapter 4 of this report.

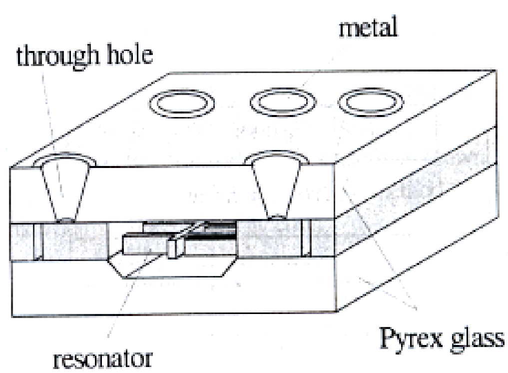

Figure 6.6. Glass micromachined packaging (Murata).

Synchrotron Radiation (LIGA) and Associated Processing

LIGA facility

Ritsumeikan University has a significant investment in infrastructure that enables the so-called LIGA process (Lithography, Electroplating, Molding). The synchrotron ring (Figure 6.7) is based on a superconducting magnet that allows a relatively high beam energy to be achieved in a relatively compact machine. A variety of structures beyond the typical extruded 2-D LIGA shapes are being realized. One method employs depth control through varying the exposure. Another method uses direct ablation of material at arbitrary angles of tilt and rotation.

Applications being developed at Ritsumeikan University for this fabrication technology include micro lens arrays, a PMMA micro capillary array chip, mechanical socket and plug connectors, a device with tunable acoustic absorption characteristics created using an array of Helmholtz resonators with mechanically adjustable cavity lengths, and thick-film magnetic cores for use in lightweight power supplies.

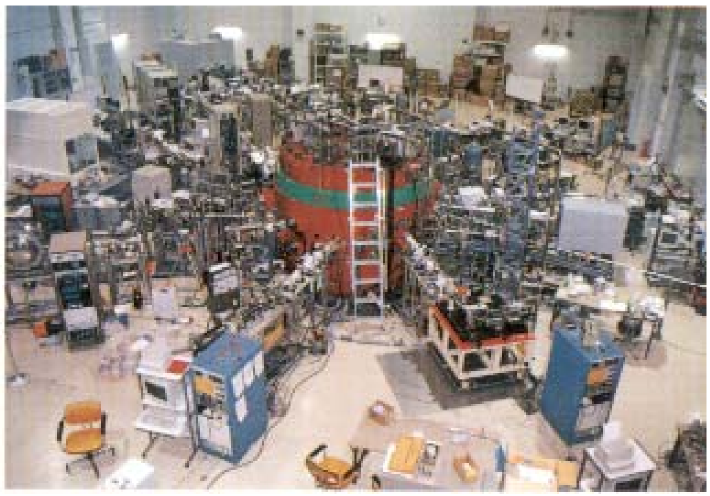

Figure 6.7. Synchrotron at Ritsumeikan University.

Associated beam lines and advanced lithography

The beam lines associated with the synchrotron were being utilized in three ways: "standard" LIGA exposure of thick resists, precision-positionable moving sample stages for 3-D exposure of thick resists, and lines to perform physics-based experiments enabled by high energy X-rays. A variety of resists were being examined, ranging from the standard thick PMMA followed by electroplating, to direct synchrotron-beam writing of polytetrafluoroethylene (PTFE — Teflon) materials (Figure 6.8).

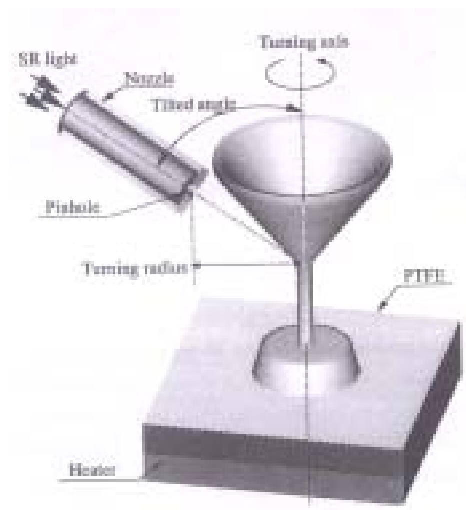

Figure 6.8. Schematic diagram of experimental setup for synchrotron ring beam direct writing (Ritsumeikan University).

LIGA supplemented by foundry CMOS

The potential of performing LIGA technology on foundry-fabricated CMOS circuitry was advertised as 'coming soon,' to realize highly-electrically-integrated, LIGA-based microsystems. In parallel with this effort was a development effort to make available foundry-based LIGA services to the outside community. Foundry-based LIGA services are expected to be generally available in the 1-2 year timeframe.

Nanochemistry Fabrication

If microsystems is 'a way to make things' based on lithography and semiconductor-related processes, nanosystems might be considered a way to make things based on chemistry-induced molecular assembly. Such work is being aggressively pursued in the United States and is also proceeding in several laboratories in Japan. As an example, the WTEC panel saw some research on nanochemistry-based fabrication, where it is possible to build nano-chains relying solely on thermal and chemical interactions—MEMS or NEMS in a beaker. The work of Profs. Kohno and Takeda at Osaka University on silicon-silicon dioxide nanochains is of particular note. They discovered in 1998 that these unusual structures form spontaneously using a modified vapor-liquid-solid growth procedure. Recently, they have developed considerable insight into the growth mechanism and have applied this knowledge to obtain high yields of nanochains. The process (Kohno, Iwasaki, and Takeda 2000) consists of heating a sample of {100} oriented silicon that is coated with 10 nm of gold and a small piece of (typically) lead in a closed ampoule at a pressure of around 10 μTorr. The sample was then moved to a new ampoule, evacuated to about the same pressure, and heated to 1230°C for two hours. The proposed mechanism for nanochain formation is periodic instability in the contact angle of the gold-silicon droplet, resulting in a variation in the diameter of the growing nanowire. Oxidation of the nanowire's surface, owing to oxygen outgassing from the glass ampoule, converts the thin sections into silicon oxide and the formation of the string of silicon nanocrystallites. For a typical growth condition, the diameter of the crystallites is about 10 nm, and the spacing is about 35 nm. The tiny amount of added lead modifies the interface tensions during nanowire growth. High yield growth of a dense carpet of nanochains can be achieved through this process.

Professor Takeda's group is investigating the optical and electronic properties of nanochains. Discovering and understanding the self-organizing formation of periodic structures is clearly an important advance in nanotechnology and in fabrication technology generally.

Ferroelectric Thin Films

Japanese researchers are depositing ferroelectric thin films using many different approaches (e.g., pulse laser deposition, sol-gel, metal-organic deposition), in addition to the thin film sputtering approach that is more common in the United States. In particular, Professor Okuyama's group at Osaka University has focused much of its effort on fabrication using non-standard IC materials including ferroelectrics and on the application of ferroelectric technology to MEMS devices such as sensors or actuators. Figure 6.9 illustrates some of the work of the Okuyama group in fabricating micromachined ferrolectric bolometers, which can be applied to the development of non-cooled infrared detectors.

Micro-stereolithography

Stereolithography is the selective, light-induced polymerization of appropriate resins by the accurate positing of impinging laser beams. Japanese researchers have been investigating the limits of this technology to create extremely small structures. The laboratory of Prof. Ikuta at Nagoya University has been a leader in this area. Current applications of this technology involve the fabrication of biochemical 'IC-chips' for microfluidics, microreactors, and microanalysis systems.

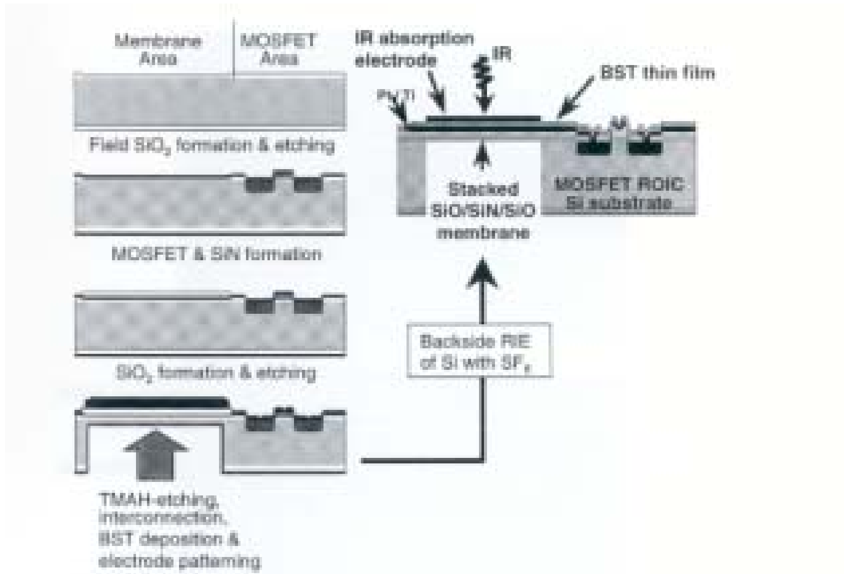

Figure 6.9. Monolithic process sequence in the fabrication of micromachined ferroelectric bolometers (Osaka University).

Injection Molding of Metals

Researchers at ISEMI (a METI lab) are working on the development of molds for vacuum casting metals using deep reactive ion etching to form channels that are later filled by injected metal using a vacuum casting process at a small company called Optnics Precision (see http://www.d1.dion.ne.jp/~rtc/). The vacuum casting process requires one hour, which is much faster than the many electroplating steps that would be needed to form the structures conventionally. ISEMI also is involved in developing a low-cost 8 x 8 MEMS optical switch using plastic microforming and “pop-up” mirrors. Embossing and injection molding is done at small companies; mold fabrication may be done at Ritsumeikan University using the LIGA process.

V-groove Technology for Optical Alignment

Professor Fujita’s group at the University of Tokyo has developed a 3-D packaging process that utilizes a micromachined wafer as a backplane for interconnecting electrical, optical, and mechanical microdevices with the external world. In this system, arrays of MEMS chips plug into a back plane using a V-groove-based latching mechanism. This packaging/assembly methodology has been demonstrated to achieve 10 micron alignment. Other applications of this approach have been mentioned above.

Plastic Treatment

Researchers at Sony have developed a method for ion implantation in plastics (Tonosaki et al. 2001) with some practical applications for impact-resistant plastic hard disks (plastics sensitive to metal). Compared to semiconductors, ion implantation on plastics requires low temperatures (<100°C) and no need for damage annealing. See the Sony site report in Appendix B for more details.

Polymer Gel Fabrication

Professor Shoji’s work at Waseda University (see above) also includes the development of a microfluidic check-valve based on laser-induced thermal gelation of methyl cellulose (Tashiro, 2001).

OVERALL IMPRESSIONS

As indicated above, Japanese researchers are developing a rather wide variety of what U.S. researchers might consider unconventional processes and materials for MEMS device fabrication. The variety of alternative approaches being considered is impressive. “Standard” thin film MEMS processing is present in Japan as well, but appears to be much less strongly emphasized than in the United States.

In general, the WTEC panel saw a lot of assembly, components, and devices. In many institutions, relatively inexpensive or older fabrication tools are being used to produce very nice results. Significant new investments are also being made in MEMS fabrication tools (e.g., ICP machines at Tohoku University, a superconducting synchrotron with advanced beam lines and rotating lithography at Ritsumeikan University, and E-beam and nanolithography tools in a variety of institutions). Even more significant, many institutions boast excellent analysis and measurement systems (e.g., multi-hundred-gigaflop fluid analysis systems at Hitachi, TEM facilities at Osaka University, and analysis systems at Waseda University). One potentially important development the panel observed was the inception of MEMS foundry services in Japan.

Perhaps what is equally important is what the panel did *not* see, although again it must be emphasized that our coverage of Japanese research was necessarily incomplete. We did not see: much use of the latest plasma tools (e.g., ICP); much research on silicon surface micromachined MEMS (with the notable exception of Omron’s “harvest” investment in bulk etching spurred by the MITI project); or many integrated MEMS or highly integrated systems. As an example, our Hitachi hosts commented that the company is no longer making airbag accelerometers, because ‘others can do it at lower cost.’

CONCLUSIONS

The Japanese definition of microsystems technology and MEMS reflects a unique Japanese perspective on the need for alternatives to the silicon and lithography-based approaches that are so strongly emphasized in the United States. It also reflects the 10-year legacy of the Micromachine Project’s funding in non-lithography-based, device-focused approaches and the project’s application thrust areas (e.g., pipe-inspection, catheters, and the attempt to demonstrate a microfactory). Many U.S. researchers, including the WTEC panelists, accept (and endorse) the broader Japanese perspective, which is essential if the “S” (systems development) in MEMS is going to be realized.

A relatively new issue that has arisen is the boundary between “micro” devices and “nano” devices. Certainly it is not size; it would be difficult to defend the assertion that a device 999 nm in size is ‘NEMS’ while 1000 nm is ‘MEMS.’ Even the ‘manufacturing’ separation of lithography versus molecular assembly suggested above is blurred when one recognizes that these techniques are often combined in the manufacture of *systems*. This awareness is also the view of many Japanese researchers, i.e., that these domains are inextricably linked and that there is no clear dividing line between “micro” and “nano.” The panel did not see much in the way of explicit “NEMS” R&D in Japan, although the work observed at Osaka University on “nanochains” was impressive. Professor Esashi also presented an interesting paper at IEEE MEMS-2000 (Miyashita, 2001) on carbon nanotube resonators. Japanese researchers seem well positioned to move ahead quickly in NEMS, given their excellence in doing aggressive “build & test” R&D. The availability of excellent analytical equipment for nanoscale research will be a big advantage as well. The panel noticed particularly outstanding facilities at Tokyo University, Tohoku University, and Osaka University.

Many of the Japanese researchers who spoke with the panel felt that Japan on the whole is not leading the world in silicon micromachining technology. However, there are notable centers of excellence in this area in Japan—in particular the work of Professors Esashi and Fujita. Japan has also contributed significant innovations in new materials, processes, and equipment. Japanese contributions include developments in wet bulk processing, dry bulk processing, surface processing, and LIGA. LIGA innovations are focused on lower cost fabrication of “traditional” projected structures through lower capital cost equipment, thereby enabling the establishment of LIGA foundry services for Japan; and on advances in X-ray mask fabrication, beam lines, and sample holders that enable the fabrication of complex, 3-D devices.

One should not underestimate the potential importance of the development of low-cost precision plastic parts for microfluidics applications. The reusable plastic connectors developed by Prof. Kitamori (see above) cost over ¥1000 in small quantities, but the cost could be reduced to less than ¥1 per unit if replicated using a LIGA technique.

The Japanese in general are very strong in non-silicon technologies. Murata is a center of particular excellence in ceramics. Integrated "PC board" fluidics work at Hitachi, KAST, and Waseda University was also particularly impressive.

The panel saw some evidence of an entrepreneurial MEMS specialty manufacturing business developing in Japan, with small companies spinning off from and sub-contracting to projects at KAST and ISEMI, for example.

There is relatively little public information on Japanese packaging and encapsulation technologies, for obvious proprietary reasons. The wafer bonding work at Tohoku University is one notable exception. The panel did not see much in the way of assembly technologies, with the exception of lamination for fluidics, and dense hybrids at Murata.

In conclusion, Japan appears to have taken a leadership role in non-Si MEMS technologies. The U.S. MEMS community should take note, given the importance of these technologies for micro*systems*, as opposed to "only" discrete MEMS devices.

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CHAPTER 7

EMERGING APPLICATIONS RESEARCH IN JAPAN—MICROFLUIDICS AND BIO-MEMS

Mineo Yamakawa

MICROFLUIDICS AND BIO-MEMS AS EMERGING FOCUS AREAS IN MEMS

The apparent, perhaps as well as hidden, messages from our visits to cutting-edge academic MEMS research labs and leading-edge industries engaged in MEMS in Japan unequivocally created rapid flashbacks and reassuring reminders. We were pleased to see some of *what we had heard about*, *what we had talked about*, and *what we had thought about* in the United States, already being under development, working as a prototype, or available as actual products in Japan.

At many of the sites the WTEC panel visited, a significant shift in the long-term applications focus had occurred explicitly towards bio-MEMS and microfluidics, which seemed to be receiving active funding and support. Notably the research includes microfluidic MEMS development for chemical analysis (e.g., DNA analysis, protein analysis/proteomics, environmental analysis, etc.), integration into Lab-On-A-Chip and a variety of bio-MEMS (e.g., microTAS, modular microfluidic components, etc.), and medical devices (e.g., diagnostic, a point-of-care, etc.).

Cross-discipline MEMS research *en route* to innovative microfluidics and bio-MEMS development was prominent in Japan, especially in taking new approaches such as inorganic/bio-organic interfaces and hybrids as well as biomimetic engineering. The panel encountered highly sensitive molecular detection, mixing and controlling of micro-volume fluids and a multi-phase flow, and highly integrated and/or highly parallelized on-chip processing for chemical analysis.

In contrast, the panel did not observe much indication of RF MEMS-related activities and plans, or even discussions about them among the researchers during the visits. The only hint of RF MEMS activities in Japan we identified seems to be a casual mention of a potential interest in “switches” by Murata and the “switch project” in Prof. Esashi’s lab at Tohoku University. For now, we have to conclude that RF MEMS activities in Japan are either invisible/hidden or just low profile, being tentatively expressed as “no plans.”

The following report, therefore, recollects some interesting technological highlights from MEMS research labs we visited in Japan, specifically focusing on the microfluidics and bio-MEMS areas of current research activities.

HITACHI (IBARAKI)—MECHANICAL ENGINEERING RESEARCH LABORATORY

Hitachi Mechanical Engineering Research Laboratory indicated that the main motivation of microfluidics and bio-MEMS activities there mainly came from the needs of environmental issues and rapid medical diagnostics applications. Hitachi has commercialized a compact water quality analysis system (Type AN-530), based on a MEMS microfluidic chip to measure such parameters as residual chlorine content, turbidity, and chromaticity, integrated with an associated reagent mixing chip and an integrated optical spectrophotometric sensor chip (Okumura et al. 2001; Miyake et al. 2001). Hitachi has plans for several components for development for MicroTAS and microfluidic devices for chemical processes, including pneumatically-actuated Si diaphragms, micropumps based on piezoelectric disks, multi-stack laminated flow channels with valves, and siloxane-based separation microchannels (Yahamakawa et al. 2001). Their chemical processing systems effectively integrate micro-absorption modules, micro-extraction modules, and/or micro-concentration modules for on-site monitoring, or in medical diagnosis for point-of-care and proteomics systems. Hitachi also has a plan to further increase efforts in microfluidics and bioanalysis such as DNA analysis and DNA sequencing in addition to proteomics analysis. In response to the question, “Why do more sequencing after human genome has been sequenced?” Hitachi indicated the need for further long-term DNA sequencing of rice, plants, and other foodstuffs. The Japanese population is reportedly sensitive to genetic modifications (GMs) of foodstuffs found abroad. In particular, the identification of GMs in rice crops seems to be an integral part of the screening processes used by grain importers/traders and in government regulatory operations.

KANAGAWA ACADEMY OF SCIENCE AND TECHNOLOGY (KANAGAWA)—*PROFESSOR KITAMORI (UNIVERSITY OF TOKYO)*

Professor Kitamori’s Integrated Chemistry Project at the Kanagawa Academy of Science and Technology focuses on standard MEMS fabrication techniques to form microfluidic platforms with highly innovative and integrated chemistry for disease diagnosis. These projects include microfluidics devices for 1) a cancer marker (e.g., “CEA”) detection system with reduced assay time from 2-3 days to 30 minutes; 2) environmental protection such as water quality assurance by detecting heavy metal (e.g., cobalt); 3) cell-based biochemistry; and 4) combinatorial chemistry, focusing on chemical synthesis using the multiplexing microflow systems to overcome the conventional limitations of capillary electrophoresis-based approaches to the aqueous environment with ionic species and fluorescence-based detection methods. The group uses glass as a substrate, with vertically stacked, interconnected chips to increase the number of flow inputs and outputs in channels of 10-200 μm in diameter. In particular, the group is exploring “nanocapillaries” where the behavior of water clusters constrained by the capillary walls becomes unconventional, leading to a longer decay constant for fluorescence. In order to connect the microflow chips to conventional microtubing, very small, precisely machined reusable plastic connectors are used. A small local company machines them nearby.

Professor Kitamori has also developed microfluidic structures to support micro-unit operations and continuous flow chemical processing. Micro-diffusion mixers have been implemented by guide structures of ~5 μm in height etched into the microchannel to maintain separation of flow streams. *In situ* fabrication of a nylon membrane was demonstrated by polymerization at a flow interface between two streams. A particularly impressive demonstration was the co-axial flow of an air stream surrounded by fluid in a microchannel driven by a syringe pumps with a pressure of several atmospheres at the inlets.

Professor Kitamori has also developed a thermal lens microscope (TLM) as a complement to fluorescence-based detection of molecules, with its refinement being capable of detecting on the order of 1-10 molecules (Uchiyama et al. 2000). TLM is based on the physical principle that molecules emit heat to the surrounding fluid when they absorb optical energy, creating a temperature profile in the fluid that causes a change in the refractive index and a transient optical lens. The change in focus can be detected using a confocal microscope at a different wavelength, thereby indirectly sensing the molecule of interest. The technique is non-specific, so the microfluidic system must be used to select the molecule of interest, and temperature sensitivities of ~1 μK are needed to detect single molecules. Special lenses for the TLM are provided in the glass chip, and these lenses are Selfoc™ optical communications components made by Nihon Sheet Glass.

MICROMACHINE CENTER (TOKYO)

The project areas related to microfluidics and bio-MEMS activities at the Micromachine Center were presented as the Intraluminal Diagnostic & Therapeutic System, one of the three conceptual systems explored as the only proposed areas of study in the first phase (of two phases, each 5 years long) initiated in 1991. However, the budget for this area was not significant: only the elemental technologies were funded, but not the system development.

OLYMPUS OPTICAL (TOKYO)

Olympus researchers at the Corporate R&D Center described their goal as being to establish the elemental technology for realizing a micromachine (i.e., MEMS) that can work in "restricted" areas, e.g., diagnosis and treatment within the human body. Their core applications and developments during the past decade have included medical applications such as endoscopes, catheters, tactile sensors, and chips for DNA testing along with associated microfluidics. The endoscopes and catheters have been developed for medical and industrial use where both have common functional features such as actuators for manipulation and control, piezoelectric contact sensors for navigation, light/vision devices to measure important parameters, and devices for repairing damaged parts.

Olympus's views of micromachines features are as follows: 1) working in tight, complicated areas for minimally invasive diagnosis and treatment and creating thinner, more sophisticated endoscopes; 2) enhanced portability such as a smaller information system; and 3) micron-level control such as cell or DNA manipulation, including a device integrating microfluidics with electro-osmotic flow for chemical analysis. For DNA analysis and proteomics, bio-chips for DNA and chemical testing/analysis based on free-flow electrophoresis for rapid sample preparation have been developed and prototyped.

OMRON (KYOTO)

Omron focuses on industrial and automotive pressure sensing and acceleration sensing and on medical devices. Since the piezo-resistive pressure sensors were first produced in 1981, followed by a capacitive pressure sensor (1994) and a "glass-silicon-glass" capacitive accelerometer (1995), the major applications have been blood pressure monitoring, leak detection, and suspension control for automotive. Finger-type blood pressure sensors are Omron's current MEMS medical products. Their future product interests are motion sensors, RF MEMS, DNA chips, microTAS, the components for game applications, IT, and biology markets.

TOHOKU UNIVERSITY (SENDAI)—*PROFESSOR ESASHI*

Professor Esashi's group has a long history of successful technology transfer dating back to the 1970s and of the productization of his research outcome such as the portable pH sensor based on an ion-sensitive FET. A capacitive pressure sensor developed at Tohoku University was the basis of several products of the Toyoda Machine Works. Another commercial development was an immobilized enzyme based biosensor for detecting "pylori" bacteria, which is the cause of many stomach ulcers. Olympus and Nihon Kohden already have products based on this device. Recently, shape-memory actuators (e.g., coil and spring) were used to make a steerable catheter with 0.5 mm outer diameter. Dr. Yoichi Haga, a medical doctor working at NICHE (described in Chapter above), is launching a spin-off company to commercialize the active catheter.

WASEDA UNIVERSITY (TOKYO)—*PROFESSOR SHOJI*

Professor Shoji's research focuses on microfluidics, using a variety of substrates such as polymer, silicon, Teflon, and glass. A particularly unique development is the use of a Teflon-like membrane in bio-MEMS. This Teflon-like membrane is deposited by spin-coating at Asahi Glass Company ("Cytop membrane" is the brand name). Professor Shoji has developed a microfluidic check-valve based on PDMS soft lithography, which was presented in the recent MicroTAS conference. His group is developing a modular approach to enable System-On-Chip ASIC-style microfluidics. A library of building blocks of pumps, valves, reactors, separators, and sensors is being designed and tested. His group has also integrated an antibody array as a surface coating on a PDMS substrate, permitting high throughput antibody-based screening of biological fluids as they flow through a microchannel, primarily for protein detection applications. Professor Shoji, collaborating with Professors Ikuta and Kitamori of Kanagawa Academy of Science and Technology, is also interested in chemical synthesis applications for the system based on the microfluidic building block library.

Professor Shoji also collaborates actively with Olympus in the such bio-MEMS areas as the development of an on-chip bioreactor, which is a PCR chamber on a chip funded through the Japanese government's Bioinformatics Initiative (mostly for DNA analysis). He commented that Olympus seemed to work with many universities on bio-applications of MEMS.

Professor Shoji also presented cell sorters using a thermal sol-gel transition where a laser-driven microfluidic valve developed in collaboration with Olympus. The valve works through laser-based heating that is used to trigger gelation of methylcellulose, which in turn blocks a microchannel. The gelation is reversible by cooling, permitting the valve to be turned on and off repeatedly by laser beam. When the gelation site is placed at a T-intersection, a multiplexor-style switch is formed.

UNIVERSITY OF TOKYO (TOKYO)—*PROFESSOR ANDO*

Professor Ando's lab focuses on the "entire" sensing system. MEMS miniaturizations of subcomponents as well as an integration of biomimetic principles bring novel functionality in the bio-MEMS projects.

Based on the human eye's involuntary eye movement to extract correlation signals, Professor Ando has developed a correlation image sensor in which the relative magnitude of adjoining pixel is measured (Ando 2000). Coupled with a vibrating mirror (at 240 Hz), this system simulates the effect of involuntary eye movement to accomplish real-time image processing such as edge detection, ranging, and spectral image matching. The latest sensing chip integrates the image sensors directly with the correlation processing circuitry with the further aim to integrate the vibration actuators with the sensors.

Inspired by the human cochlea, the Fishbone sensor (Tanaka, Abe, and Ando 1998), mechanically separates an audio signal into its frequency components (1998). Used in conjunction with a logarithmic spiral reflector, this decomposition of the audio signal could be used to accomplish sound source localization. If used in reverse by actuating the "bone" fingers, in turn, the structure could be used to generate a single impulse. The cochlea has also been the inspiration for auditory scene analysis algorithms based on decomposition of volume, pitch, and timbre. Finally, other types of direction-sensitive audio detectors have been demonstrated that mimic the ears of a barn owl and a fly.

The group also has developed a number of robust tactile sensors that take various approaches to sensing the deformation of a layer of silicone, which would be applied to the surface of the sensing appendage. The latest sensor principle achieves six-axis deformation sensing by launching ultrasonic waves from a 2 x 2 transmitter array and measuring the waves with a similar receiver after they have traversed the medium (Ando et al. 2001).

Extending the work in tactile sensing, the group is now investigating methods of generating tactile feedback. In one device, a SAW device is used to modulate the stick-slip behavior of a slider on its surface. As the slider is pushed around by the user, the perceived surface roughness can be modulated by changing the SAW frequency. Another device launches ultrasonic waves at the user's finger under water to produce tactile (Nara et al. 2001).

MICROFLUIDICS AND BIO-MEMS PROJECTS IN OTHER LABS

At Ritsumeikan University (Professor Sugiyama), among a number of applications of the LIGA, the bio-MEMS application was a Lab-On-A-Chip DNA analysis demonstrated in a PMMA micro capillary array. In addition, a device with tunable acoustic absorption characteristics was created using an array of Helmholtz resonators with mechanically adjustable cavity lengths, which potentially could lead to some biosensor applications.

At the Laboratory for Integrated Micro-Mechatronic Systems of the University of Tokyo's Center for International Research on MicroMechatronics, Professor Fujita briefly described several on-going bio-MEMS and microfluidics projects such as biomicrosystems for cells manipulation, MEMS applications to the gene transfer, a neural growth biomicrosystem, and the design and realization of a robotics device for depositing pico-liter volumes of liquid.

In response to our inquiry, Mr. Matsumoto of Sony Corporation mentioned "ePrint company" as their external collaboration on a microfluidics project with Professor Esashi (Tohoku University). No other microfluidic or bio-MEMS projects were mentioned.

CONCLUSIONS

The WTEC panel found no big surprises during the visits, but found many quality innovations in emerging MEMS applications research in the microfluidics and bio-MEMS areas with increasing funding and support in Japan. We identified a big push to advance basic microfluidics MEMS technologies toward the highly integrated, modularized, and/or parallelized platforms for chemical and bio-analysis, microTAS, and diagnostic medical devices with innovative new approaches as described above. Microfluidics and bio-MEMS are no longer subsumed as ancillary applications of MEMS, but are gradually becoming a mainstream enabler for MEMS applications research in Japan. In contrast, current RF MEMS activities in Japan seem to be invisible/hidden or potentially at the "getting ready stage."

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CHAPTER 8

CONCLUSIONS

Roger T. Howe

ASSESSMENT OF MICROSYSTEMS TECHNOLOGY IN JAPAN

Japan has been a major participant from the earliest days in the field of microelectromechanical systems (MEMS) or microsystems. Researchers in Japan have made key contributions to new actuation principles, to new transduction materials and principles, and to the application of microsystems in the automotive, biomedical, and consumer electronics industries. The panel's visit to Japan in November 2001 coincided with a period of transition, in which the 10-year MITI Micromachine Technology Project was ending and new research initiatives were being organized. As a result, we had the opportunity to visit and interact with leading Japanese researchers who were in the process of reevaluating where their research programs should be directed in the coming decade.

We found that Japan is moving closer to the U.S. model of microsystems research funding, in which a narrower target application is clearly identified and an explicit goal is transition of the technology into industry. In the case of the new five-year METI microfluidics project just getting underway in early 2002, it remains to be seen how the project is implemented, the respective roles of universities versus companies, and whether or not the funding is concentrated in several centers of excellence. It is encouraging that one of the leading researchers in microfluidics, Prof. Kitamori from the University of Tokyo and KAST, will have a role in organizing the project. In previous major projects, funding was often determined by government bureaucrats and spread over too large a number of companies to have a significant impact on the research agenda of any one of them. For example, the recently completed Super-Eye Project involved well over a dozen companies and universities in the Osaka area, each of which received a small portion of the budget. An encouraging example of Japan's ability to be more selective and support outstanding research groups with adequate resources is the funding of major new fabrication facilities at Tohoku University and University of Tokyo in the late 1990s.

Increased funding in nanotechnology in Japan is likely to lead to rapid advances in new materials for microsystems. Many Japanese researchers have a very aggressive "build and test" approach to developing fabrication processes for new materials, which will work very well at the intersection of nanotechnology and microfabrication. Recent results from Tohoku University on evaluating hydrogen storage in carbon nanotubes is an example of this cross fertilization from a leading microsystems group's experience in microfabrication and metrology to a new application for a synthetic nanostructure. Additional initiatives that may start in 2002-2003 include a Ministry of Agriculture program in cell-based biochemistry and a program in micro power generation. In summary, the level of funding should be adequate to support research and development at the leading institutions, with the applications focus shifting to microfluidic systems and bio-MEMS.

The Japanese university laboratories that we visited are all doing outstanding, "world-class" research in microsystems, which is definitely having an impact on Japanese industry. The mechanism for transferring technology from universities to industry is completely different from that of the United States. In general, Japanese companies are comfortable with sending researchers to spend one or two years in academic laboratories, where they typically work on a specific project, but are also exposed to a wide range of research related to microsystems. These researchers return to the company equipped and more importantly, energized to work on microsystems applications, having absorbed some of the background, experimental know-how, and vision from the university research group. In contrast, in the United States, graduate students and faculty typically form a start-up company that attempts to commercialize academic research using funding by venture capitalists. The start-up company usually does not complete the process of commercial development by marketing products, but instead is bought by a large company before it has its initial public offering. In the majority of these academic start-ups, intellectual property is licensed from the university.

Over the past two years, Japanese public universities have formed technology licensing offices (TLOs), whose charter is to license intellectual property held by the university. We found that this change has had an impact on the behavior of academic researchers, some of whom are now actively seeking patents for their inventions. However, the funding levels of the TLOs appear generally inadequate, and so relatively few patents can be filed. The TLOs may also introduce friction into the customary interactions between Japanese industry and the academic research groups, in particular for those groups with a number of visitors from different companies. Tohoku University's NICHE Laboratory attempts to head off conflicts of interest by keeping all work in the lab completely open to all lab members, whether from industry or graduate students. Inventions made at NICHE are shared between Tohoku and the company. The U.S. experience in microsystems indicates that the formation of aggressive TLOs does not necessarily lead to ease of technology transfer.

University education in microsystems in Japan consists largely of isolated courses rather than an integrated curriculum, which is similar to the situation in the United States. The presence of significant numbers of foreign students and visiting researchers from Asia and Europe is an important development for Japan that will yield long-term benefits through close ties to researchers in other countries. The outreach efforts of microsystems researchers to the general public, and especially to K-12 students, are much more extensive than in the United States. In addition to the Micromachine Center's picture contest for elementary school students, Ritsumeikan faculty present their research projects to students in affiliated secondary schools, and Prof. Fujita of the University of Tokyo has played a key role in an exhibit on microsystems at the Museum of Emerging Science and Technology in Tokyo.

The foundry infrastructure in Japan is less well developed than in the United States, although several companies have announced foundry services in Fall 2001 and a LIGA foundry service will be started at the Ritsumeikan University synchrotron in 2002. The recent conversion of captive microfabrication facilities into foundries is motivated by the need to make money from under-utilized, expensive infrastructure. The large variety of micromachining processes used by Japanese academic and industrial researchers has been an impediment to establishing standardized processes. In contrast, the polysilicon surface micromachining foundries from Cronos (MUMPS) and from Sandia National Laboratories (SUMMIT) have resulted in large user communities in academic and industry. Several researchers mentioned that they would support establishing a Japanese equivalent to the MEMS Exchange as an impartial broker for process services. In the case of non-silicon microfabrication techniques, AIST is developing low-cost technologies for microsystems based on a network of small specialty manufacturers. This capability does not exist in the United States and is a definite competitive advantage for many microsystem applications, such as microfluidics.

Another aspect of infrastructure is the establishment of standards for microsystem technologies. Worldwide, the lack of standards for either fabrication and packaging technologies or for test procedures is recognized to be an impediment to the commercialization of microsystems. In Japan, the Micromachine Center is developing a set of standards for thin-film testing, in collaboration with NIST in the United States and NEXUS in Europe.

Japanese industry in general has taken a "wait and see" attitude toward microsystems applications that may be due partially to the Micromachine Technology Project, which pursued long-term objectives rather than commercial opportunities. In general, microsystems tend to be an enabling technology and not to lead directly to stand-alone, high-volume, high-profit applications. Nevertheless, we found excellent work in both microsystems technology and a variety of applications in Japanese companies. In the case of Omron, there is a clear corporate vision or roadmap for the development of microsystems technology and its insertion into existing and new products. Most large companies tended to have isolated efforts centered around one application.

bio-MEMS and microfluidics are the focus of much of the long-term applications research at the sites we visited. It is not coincidental that the new METI project is concentrating on these areas, which are also the subject of large public and private investments in the United States and Europe. The Japanese research groups that we visited are doing excellent work in microfluidics, with some interesting new approaches being explored for molecular detection, mixing, and multi-phase flow. In the area of medical instruments, Olympus is continuing to fund research in actively steered catheters with more sophisticated functionality.

Japan's principal advantage in microsystems technology is rooted in a general willingness to use any appropriate materials or technologies to achieve the necessary performance or function. This pragmatic approach contrasts with the U.S. tendency to concentrate on silicon-based planar batch fabrication. The difference in perspective is due to the roots of Japanese microsystems being in robotics and mechanical engineering, whereas the origins of U.S. microsystems lie in integrated-circuit technology. Over the past few years, these differences have become less distinct, as the United States pursues applications requiring non-silicon materials, such as micro power generation.

At the sites we visited, we saw a wide variety of process tools, including LIGA and its extensions, micro stereolithography, and e-beam lithography. We found that the range of materials under study in Japan was significantly broader than in the United States, with more activities in piezoelectrics, polymers, and ceramics. Although there was equipment for thin-film deposition and etching, these surface micromachining processes were not as dominant as in the United States. The analytical equipment, such as TEMs and AFMs, was superior to that available in U.S. academic labs. Very little work is being done on integrating CMOS and microstructures by co-fabrication, in contrast to long-term research and development in the United States and Europe.

Japanese industry has a large number of very small companies that specialize in precision machining technology. By contrast, the United States has very little capability in this area. The Japanese companies are increasingly becoming involved in microsystems development. AIST's ISEMI lab is launching a program to coordinate such specialty manufacturers and to develop a low-cost, possibly plastic-based, microfabrication capability. The impact of this program on demonstrating pathways toward the cost-effective commercialization of microfluidics could be very significant. Since planar microfluidic circuits must have interconnections to conventional fluid-handling equipment, the availability of precision parts and the means to assemble them is essential. The module and board assembly technologies that are central to the consumer electronics industry (e.g., Murata and Sony) could be borrowed for microfluidic systems.

IMPLICATIONS FOR THE U.S. MEMS AND MICROSYSTEMS R&D EFFORT

The panel sees several policy implications of this study for the sponsoring U.S. organizations. The first is that the U.S. research agenda throughout the 1990s was to exploit fully those areas most closely derived from silicon IC technology. This decision resulted in successfully commercialized *sub*systems, such as the silicon accelerometers and the Texas Instruments Digital Mirror Display™. However, the real power of microsystems will only be available when a larger set of materials and processes are available to designers, along with the parallel assembly processes needed to manufacture economically.

The lack of depth in non-silicon materials, precision piece parts, and assembly technologies is a growing weakness for U.S. microsystems research. For example, several of the emerging applications now being funded by DARPA—the chip-scale atomic clock, "smart dust," and micro power systems—require the integration of silicon electronic and microelectromechanical subsystems, together with non-silicon materials. Additional support for research in new materials and in parallel assembly processes will be required, if the ambitious microsystems concepts are to become manufacturable realities. The MEMS Exchange could play a central role in promoting the use of these new materials and assembly processes by the microsystems research community. Needless to say, it will be challenging to incorporate these into an infrastructure built around wafer processing. Aligned silicon wafer bonding would be a small, but significant step toward expansion into non-planar technologies.

Nanotechnology, which is taken to mean fabrication of structures using synthetic techniques, is a promising source of new materials and surface functionalization in microsystems. Conversely, microsystems offers capabilities for the characterization of nanostructures. The key goal for U.S. funding agencies is to ensure that a significant fraction of the research projects in nanotechnology involve the microsystems research community. The NIRT program at the NSF is attempting to join science and engineering researchers in early-stage nanotechnology projects, which will do much to accelerate the application of nanostructures. In Japan, the “top-down” approaches to fabrication and the synthetic nanotechnology methods are viewed as part of a continuum, which the panel agrees is a useful perspective. In microfluidic systems, for example, nanostructures will likely be very useful as functional blocks located on surfaces within the fluid channels or perhaps distributed in the fluid itself.

Standards are barely emerging in the microsystems field, due in part to the immaturity of microsystems process technology. Largely through the efforts of NIST, the first standards have been released for thin-film mechanical property test structures. With the formation of the MEMS Industry Group in 2001, there is an excellent opportunity to accelerate the identification and definition of new standards. The need for reliability testing procedures is also critical for many emerging applications, such as RF micromechanical switches. By coordinating with the Micromachine Center in Japan and NEXUS in Europe, NIST and other U.S. standards efforts can ensure that universal standards emerge, to the benefit of everyone commercializing microsystems.

Developing a curriculum in microsystems has proven challenging, due to the interdisciplinary nature of the field and the wide variety of backgrounds of those seeking to enter it. By sponsoring a workshop on microsystems education, the NSF could make a major contribution to improving the state of graduate education in this field. By scheduling the workshop adjacent to one of the major conferences, most of the educators in the field (including those from overseas) would be able to attend.

Finally, the outreach efforts of microsystems researchers in Japan are much more extensive than those in the United States. The NSF’s education programs should consider motivating microsystems researchers to develop museum exhibits and curriculum materials for K-12 students. Given that non-electronic microstructures can be understood more easily, they tend to be more effective in sparking interest in science and technology.

APPENDIX A. BIOGRAPHIES OF PANEL MEMBERS

Roger T. Howe (Panel Chair)

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Prof. Roger T. Howe received the B.S. degree in physics from Harvey Mudd College, Claremont, California, in 1979 and the M.S. and Ph.D. degrees in electrical engineering from the University of California at Berkeley in 1981 and 1984. He was on the faculty of Carnegie-Mellon University during the 1984-85 academic year and was an assistant professor at the Massachusetts Institute of Technology from 1985-87. In 1987, he joined the Department of Electrical Engineering and Computer Sciences at the University of California at Berkeley, where he is now a professor, as well as a Director of the Berkeley Sensor & Actuator Center. In 1997, he was appointed a professor in the Department of Mechanical Engineering.

His research interests include micro-electromechanical system (MEMS) design, micromachining processes, and massively parallel assembly processes. He served as co-general chairman of the 1990 IEEE Micro Electro Mechanical Systems Workshop (MEMS 90) and as general chairman of the 1996 Solid-State Sensor and Actuator Workshop at Hilton Head, South Carolina. He is an editor of the IEEE/ASME *Journal of Microelectromechanical Systems*. He was elected an IEEE Fellow in 1996 "for seminal contributions to microfabrication technologies, devices, and micro-electromechanical systems." He is co-recipient with Richard S. Muller of Berkeley of the 1998 IEEE Cledo Brunetti Award "for leadership and pioneering contributions to the field of micro-electromechanical systems." He is the co-author, with Prof. C.G. Sodini of MIT, of *Microelectronics: An Integrated Approach*, Prentice Hall, 1997, an undergraduate textbook.

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Dr. Mark G. Allen received three bachelor degrees from the University of Pennsylvania in 1983: the B.A. in chemistry, the B.S.E. in chemical engineering and the B.S.E. in electrical engineering. Following this, he received the S.M. and Ph.D. degrees in microelectronic materials from the Massachusetts Institute of Technology in l986 and 1989 respectively. He joined the faculty of the Georgia Institute of Technology after a postdoctoral appointment at M.I.T.

Dr. Allen participates in the Microsystems Research Center and the Packaging Research Center. His main research focus is in micro-electromechanical systems (MEMS), which is defined as the use of microfabrication techniques to create mechanical structures in silicon and other materials, potentially in addition to electronic devices.

His work has received local, national, and international attention in both the popular press and in engineering trade publications. Specific research projects that have recently received media attention are 1) magnetically actuated microrelays, smaller than a dime, that have potential use in automobile electronics, test equipment, and other areas where low actuation voltages are required and 2) drug delivery via microneedles, tiny chips containing arrays of tiny needles, each thinner than a human hair, that can potentially be put on the skin for one-time injections and possibly left on the skin for continuous release of a medication under the control of a microprocessor.

Dr. Allen served as a visiting professor at the Swiss Federal Institute of Technology during the summers of 1994 and 1998.

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Andrew Berlin is a Sector Director at Intel Research and a Principal Engineer in the Microsystems Department of Intel's Technology and Manufacturing Group. Berlin manages a newly formed biotechnology research initiative that is chartered to create biomedical diagnostic chips based in part on MEMS technology. The first project in that effort, Precision Biology, is focused on creating chips capable of performing bio molecular detection with single-molecule resolution. Prior to joining Intel, Berlin led a major MEMS research program at the Xerox Palo Alto Research Center, and was one of the early PIs in DARPA's MEMS program.

Berlin received S.B., S.M., and Ph.D. degrees from the Massachusetts Institute of Technology, where his research activities included development of active structural enhancement technology, in which computation is used to augment the physical characteristics of a material. In the late 80's, Berlin was a lead designer of the Hewlett-Packard/MIT Supercomputer Toolkit, one of the first VLIW parallel processors, which was designed to provide high-performance computing power for use within scientific instruments.

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Elliot Hui received the B.S. degree in physics and the B.S. degree in electrical engineering from the Massachusetts Institute of Technology in 1994 and the Ph.D. degree in electrical engineering from the University of California at Berkeley in 2002. His doctoral research focused on assembly and molding processes for three-dimensional microfabrication of silicon and polymer structures. His current research interests involve the application of MEMS technology to liver tissue engineering.

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Dave Monk received his B.S. in chemical engineering from the University of Iowa in 1989. During that time, he worked at Rockwell International doing research with polyimide interlayer dielectrics for a silicon-on-silicon multichip module development project. He received his Ph.D. in chemical engineering in 1993 from the University of California, Berkeley, through joint work between chemical engineering and the Berkeley Sensor & Actuator Center in electrical engineering and computer science. His research emphasis there was modeling the sacrificial layer etching process for surface micromachining.

Dave joined Motorola in 1993 and worked for the first three years in the Packaging Technology Center within Motorola SPS's Sensor Products Division. His work during that time focused on media compatible packaging of pressure sensor devices. He also has led projects on tungsten silicide electronic trimming for pressure sensors, low-pressure sensors for washing machine applications, and the recent development of a CMOS integrated, surface-micromachined, absolute pressure sensor for tire pressure monitoring applications. This most recent project developed into a microsystem effort that included a MEMS-based pressure sensor, a temperature sensor, CMOS interface ASIC, MCU, and RF transmitter/receiver chipset for the tire pressure monitoring application. Currently, Dave manages a development group that includes system engineering, transducer design, ASIC design, CAD, test development, and package development for MEMS-based products (inertial and pressure sensors) within Motorola's Sensor Products Division.

Dave has been active in the MEMS/MST academic community as a participant in the technical committees for the International Conference on Solid-State Sensors and Actuators (Transducers '99 in Sendai), the Solid-State Sensors and Actuators Workshop (Hilton Head '96 and '98), MEMS 2001 in Las Vegas, and the IMAPS Sensor Division (1995 through present). He has published more than 50 technical conference papers, 10 refereed journal papers, and has six issued patents in the MEMS/MST field.

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Khalil Najafi (an IEEE Fellow since 2000) received the B.S., M.S., and the Ph.D. degrees in 1980, 1981, and 1986, respectively, all in electrical engineering from the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor. From 1986-1988 he was employed as a research fellow, from 1988-1990 as an assistant research scientist, from 1990-1993 as an assistant professor, from 1993-1998 as an associate professor, and since September 1998 as a professor and as the director of the Solid-State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan. His research interests include micromachining technologies, solid-state micromachined sensors, actuators, and MEMS; analog integrated circuits; implantable biomedical microsystems; hermetic micropackaging; and low-power wireless sensing/actuating systems.

Dr. Najafi was awarded a National Science Foundation Young Investigator Award from 1992-1997, was the recipient of the Beatrice Winner Award for Editorial Excellence at the 1986 International Solid-State Circuits

Conference, of the Paul Rappaport Award for co-authoring the best paper published in the IEEE Transactions on Electron Devices, and of the Best Paper Award at ISSCC 1999. In 1994 he received the University of Michigan's "Henry Russel Award" for outstanding achievement and scholarship, and was selected as the "Professor of the Year" in 1993. In 1998 he was named the Arthur F. Thurnau Professor for outstanding contributions to teaching and research and received the College of Engineering's Research Excellence Award. He has been active in the field of solid-state sensors and actuators for more than eighteen years and has been involved in several conferences and workshops dealing with solid-state sensors and actuators, including the International Conference on Solid-State Sensors and Actuators, the Hilton-Head Solid-State Sensors and Actuators Workshop, and the IEEE/ASME Micro Electromechanical Systems (MEMS) Workshop. Dr. Najafi is the editor for *Solid-State Sensors* for *IEEE Transactions on Electron Devices*, associate editor for the *IEEE Journal of Solid-State Circuits,* and an associate editor for the *Journal of Micromechanics and Microengineering,* Institute of Physics Publishing.

Mineo Yamakawa

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Dr. Mineo Yamakawa is a staff research scientist at the Biotechnology Research Group, currently a part of the Microsystems (MEMS) Group of Intel Corporation, located in California's Silicon Valley. He was a key core group member working to create a new bio-project at Intel with his molecular biophysics and medical research background as well as his business/product engineering management background. He is serving in an Intel Research Council AIM Steering Committee, one of Intel's organizations funding academic research projects and consortium, as well as co-chairing its Health Subcommittee.

Dr. Yamakawa received his B.Engineering in applied physics from Waseda University, Tokyo, Japan, and his Ph.D. in physiology and biophysics from the University of Oklahoma Health Sciences Center. He was a Muscular Dystrophy Association's Postdoctoral Research Fellow at the University of Pennsylvania when he joined the team to develop a series of novel "caged" nucleotides for molecular reaction kinetics using laser photolysis combined with digital signal processing for the studies of muscle contractions at molecular level. While he was developing high-resolution, ultra-sensitive transducers to measure and analyze the small force generated by isolated single smooth muscle cells, he subsequently joined the team to initiate the molecular "structure-function" studies (molecular genetics-physiology/biophysics) using Drosophilia (fruit-fly) genetic mutants at the University of Vermont. He joined Intel as a senior software development engineer for Intel-branded consumer product development, and he was an engineering manager at the Connected Product Division, the organization developing, delivering, and servicing various Intel-branded consumer products all over the world before he joined an Intel research team.

Dr. Yamakawa is a member of academic and industrial organizations, including American Association for the Advancement of Science (AAAS), the Association of Computing Machinery (ACM), the American Chemical Society (ACS), the Association for Laboratory Automation (ALA), the American Physical Society (APS), and the Institute of Electrical and Electronics Engineers (IEEE).

APPENDIX B. SITE REPORTS

Site: **Hitachi, Ltd.**
Mechanical Engineering Research Laboratory
502, Kandatsu, Tsuchiura
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http://www.hitachi.co.jp/Div/merl/index-e.html

Date visited: 16 November 2001

WTEC Attendees: M.G. Allen (report author), Y.T. Chien, R. Howe, E. Hui, and H. Morishita

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BACKGROUND AND GROUP OVERVIEW

The research laboratories of Hitachi are the major internal research arm of Hitachi, Ltd. The laboratories are organized into a Central Research Laboratory and a number of specialized laboratories (of which the Mechanical Engineering Research Laboratory, or MERL, is one.) There are several laboratories outside of Japan as well, including four in the United States, several in Europe, and a new MERL in China. In the United States, the research activities are concentrated in San Jose (semiconductor design), Santa Clara (information/networks), Detroit (automotive Products), and Princeton (digital multimedia).

The Mechanical Engineering Research Laboratory houses approximately 400 researchers. The laboratory research occurs in a broad range of primarily mechanical engineering-related areas. Examples of products developed in the laboratory include magnetic disk devices, automated teller machines (especially for handling extremely complex or worn currency; Chinese currency was given as an explicit example), color laser printers, plasma etchers for large-scale integration, optical communications modules incorporating laser welding, semiconductor packages and devices, mechanical photonic switches, thin-type compact escalators, and many other electronic and non-electronic applications.

As an example of some of the non-MEMS capabilities of the laboratory, Dr. Shigenori Togashi, Senior Researcher, gave a presentation on fluid mechanics analysis capabilities (on the large scale). The facilities for computational fluid mechanics analyses were extensive. Both 80 GFLOPS and 200 GFLOPS facilities are available to perform unsteady flow field analyses around an entire product. Smaller 16 GFLOPS and 3 GFLOPS clusters are also available for partial analysis. Examples of products that have been successfully modeled range from instability of impeller pumps and flow in a two-phase pump-suction channel to the complete flow field around a high-speed (nozomi) shinkansen (bullet train).

MEMS R&D ACTIVITIES

Microfluidics (Dr. Ryo Miyake, Senior Researcher)

Hitachi's microfluidics work is motivated by both environmental issues and rapid medical diagnostics applications. A simple sensing method for chemical substances that addresses these areas is a key technology. Hitachi's approach is to utilize a MEMS component as a key, high-value-added, and potentially replaceable portion of a larger, more valuable system.

As an example of this approach, Hitachi researchers showed one of their MEMS-based commercial products: a compact water analysis system (Type AN-530). The basic idea is to have multipoint monitoring of water quality, as opposed to a single-point monitor at the city water distribution plant. If such monitoring devices could be made small enough and sufficiently low in cost, they could be distributed along multiple branch pipes and interconnected by a data network to pinpoint water supply contamination. The core of this analysis system is a microfluidic chip that can measure residual chlorine content, turbidity, and chromaticity. Water is analyzed by bringing together reagents and sample water in a mixing chip and passing them through an optical absorptiometer to perform spectroscopic analysis.

MERL efforts are now moving toward micro total analysis systems and microfluidic devices for chemical processes. Part of these efforts is motivated by MERL's potential participation in the (smaller-scale) successor project to the MITI Micromachine Project, which will focus on biosystems. A variety of fabrication technologies for these approaches are under investigation, including pneumatically-actuated silicone diaphragms, micropumps based on piezoelectric disks, multistack laminated flow channels with check valves, and siloxane-based separation microchannels. Examples of chemical process systems under consideration include microabsorption modules, microextraction modules, and microconcentration modules. Future application areas include proteomics (i.e., protein analysis) and point-of-care systems.

Disk Drive Actuators (Dr. Masahito Kobayashi, Senior Researcher)

As track densities on magnetic disk drives increase, individual track widths shrink and the requirements on head tracking and stability increase. One MEMS application to address head stability pursued by Hitachi (as well as groups in the United States such as IBM) is to place MEMS-based micropositioners at the tip of the head positioner to allow fine control over the head position on the scale of the track width. The work performed at Hitachi utilizes PZT (lead-zirconate-titanate) piezoelectric actuators to perform the micropositioning.

Contactor Probes (Dr. Tatsuya Nagata, Senior Researcher)

In the assembly of multichip modules, the problem of Known Good Die (i.e., pre-testing of the semiconductor die prior to assembly on the module to assure high yield) is of great importance. An important issue is to determine how to test these die prior to packaging while simultaneously preserving their ability to be packaged (e.g., testing without rendering the probing pads unsuitable for subsequent bonding). Examples of chips that fall into this category are memory chips. MEMS technology has been used to create an array of high density probe tips that match geometrically the pads on typical Hitachi memory chips. Requirements for this device include fine pitch probing (85 microns), high positioning accuracy (5 micron), small marks on the LSI pad (15 microns), stable probing load (50 mN), and low contact resistance (less than 1 ohm). The device is laid directly on the test chip using chip-to-chip pressure. These devices were designed for 64 MB DRAMs, but since these are obsolete, the device is being redesigned for the next generation of DRAMS.

Optical Devices (Dr. Tatsuya Nagata, Senior Researcher)

The final presentation described MERL's efforts in optical devices. The technology is based on V-grooves anisotropically wet etched in silicon followed by installation of optical fibers and ball lenses. Thin-film metal solders are used to fasten the components together. These devices were introduced several years ago and are currently produced in another division within Hitachi.

PARADIGM SHIFTS AND OUTLOOK

MERL plans to increase its efforts in microfluidics and bioanalysis, and perhaps decrease emphasis on more traditional physical sensors. As one example, they are interested in appropriate methods for DNA analysis and sequencing. Even though the human genome has been sequenced, Hitachi feels that there are needs for other sequencing approaches to rice, plants, and other foodstuffs. They also mentioned that Hitachi used to manufacture airbag sensors but ceased this activity since they felt that their fabrication costs were higher than those of other companies in the same market. Hitachi did acknowledge that they were planning new non-bio-related projects, but the details of these projects (including potential application areas) were proprietary. In general, the projects that were observed were consistent with the theme that the MEMS components were considered as crucial, value-added pieces of larger, more expensive (and potentially more profitable) systems.

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Site: **National Institute of Advanced Industrial Science and Technology (AIST), Integrated Solid-State Electro Mechanical Instruments (ISEMI)**
Institute of Mechanical Systems Engineering
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Date visited: November 16, 2001

WTEC Attendees: R. Howe (report author), M. Allen, Y. T. Chien, E. Hui, and H. Morishita

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Also present:

Dr. Naoki Ichikawa, Group Leader, Applied Complexity Engineering Group, micro flow visualization
Dr. Sohei Matsumoto, Research Staff Member, surface activation bonding
Dr. Hideki Takagi, Senior Research Scientist, ISEMI
Dr. Xuechuan Shan, Supporting research staff, ISEMI, visitor from JINTIC, Singapore, working on optical systems.
Dr. Yang Zhen, NEDO Fellow, ISEMI, micro mixing project

BACKGROUND

In the recent reorganization of the national laboratories, the name of the Mechanical Engineering Laboratory has been changed to the Institute of Mechanical Systems Engineering. Dr. Maeda leads a research group that is called ISEMI, an acronym that honors the late Dr. Isemi Igarashi, the founder of silicon MEMS in Japan. Dr. Maeda provided a frank assessment of the 10-year Micromachine Project, which has recently ended. This project's focus was to develop a range of technologies needed to demonstrate microrobots for machine maintenance. The commercial market for these microrobots is too far in the future for it to have served as the project's goal, according to Dr. Maeda. The mix of research projects supported by the Micromachine Project was weighted too heavily toward large companies. The new strategy, which is the direction his own group is pursuing, is to focus on developing low-cost technologies for MEMS and then creating the foundry or distributed fabrication network infrastructure that will allow access to them by a large number of users in small companies and academic instructions.

RESEARCH ENVIRONMENT

Dr. Maeda's presentation provided a vision for a new strategy for MEMS research and development in Japan. He feels that AIST can be a catalyst in pursuing commercially relevant MEMS technologies, by partnering with the large number of small, specialized Japanese manufacturing companies. The latter have been recently become less dependent on large corporations, due in part to the economic downturn and to the trend to move manufacturing offshore. In order to make such collaborations work, more than one small company may need to be involved and access to specialized fabrication services, such as LIGA, is needed. Dr. Maeda is engaged in gaining AIST funding for "jump-starting" these partnerships. The network of micro and milli-machining capabilities that would result from a series of cooperative projects could lead to a powerful, low-cost manufacturing capability for MEMS in Japan.

He provided two examples to show how this new style of research partnership works: ISEMI is involved in developing a low-cost 8 x 8 MEMS optical switch using plastic microforming and "pop-up" mirrors. Embossing and injection molding is done at small companies, but mold fabrication could possibly be done using the LIGA process line at Ritsumeikan University. An Esco hot embossing machine is used with a silicon master stamp for forming microstructures in PMMA and polycarbonate substrates. Some of these processes are being done in ISEMI's own laboratory. Alignment of optical fibers to the mirror array, a critical step if the project is to achieve low manufacturing cost, is the task of a small start-up company. The second example was a multi-layer silicon circuit board that would be suitable for multi-chip modules or a dense probe card. In this case, ISEMI researchers use deep reactive ion etching to form channels that are later filled by injected metal using a vacuum casting process at a small company called Optnics Precision. The vacuum casting process requires one hour, much faster than the many electroplating steps that would be needed to form the structures conventionally.

Dr. Maeda indicated that there are many high-valued-added applications for MEMS, even some that might qualify as "killer applications." Examples given were high-resolution printer heads, high-density data storage, micro chemical reactors, and medical devices for the elderly or handicapped. By tackling the challenge of developing new low-cost, plastic microforming and metal-based micromachining processes in collaboration with small companies, ISEMI can catalyze a distributed MEMS manufacturing capability in Japan. Specific needs are the use of carbon dies for microforming glass, improved PZT piezoelectrics, and micro chemical reactors.

The research environment has a significant number of researchers from other Asian countries at the AIST, a Japanese national laboratory. The WTEC panel met visitors from China, Korea, and Singapore. The closer ties between Japanese and other Asian institutions have been a trend over the past few years.

RESEARCH PROJECTS

Dr. Maeda and his research group introduced several ongoing research projects. The first was an ultrasonic micromixing chamber for integrated chemistry chips by Dr. Yang Zhen. The second was an interesting application of microfluidics to improve the performance and reduce the size of dialysis machines. In order to de-gas the dialyte, a seal between the liquid and the ambient was achieved using hydrophobic surface coatings. A piezoelectric 2-D scanning micromirror that has a resonant frequency of 8 kHz has also been developed. With relatively low actuation voltages, the mirror achieved 40 degrees of deflection at resonance.

During the 1990s, Dr. Maeda and his colleagues developed processes for room-temperature bonding of silicon to silicon or other materials. He feels that the need for a high vacuum during the bonding process makes it impractical in the short term. The project is now under the direction of Dr. Tagaki at ISEMI.

LABORATORY FACILITIES

In touring the ISEMI fabrication and test laboratories, the panel saw a good example of a "drop-in" clean room built within the existing building. Although we didn't have time for a complete tour, the ISEMI lab has a reasonably complete set of fabrications tools for MEMS.

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Host: Prof. Takehiko Kitamori, Dept. of Applied Chemistry, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656 Japan, Tel +81-3-5841-7231, Fax +81-3-5841-6039, kitamori@icl.t.u-tokyo.ac.jp

Also present at visit to ICL at KAST:

Dr. Yoshikuni Kikutani, Research Scientist
Dr. Keisuke Morishima, Research Scientist
Dr. Manabu Tokeshi, Sub-Project Leader

BACKGROUND

Professor Kitamori is a member of the faculty of the University of Tokyo but has his main research laboratory for applied integrated chemistry at the Kanagawa Academy of Science and Technology (KAST). He began his work in analytical chemistry during his 10-year career as a researcher at Hitachi, following an undergraduate education in physics and graduate work in chemistry. He is leading a five-year project on integrated chemistry at KAST. Microfluidics and integrated chemistry will be the focus of a major METI program that will start next year. Professor Kitamori will play a leadership role in this initiative. Another potential initiative is in microfluidic systems for cell-based biochemistry, which could be the focus of a Ministry of Agriculture program starting in 2003.

Research Environment

The laboratory at KAST is where Prof. Kitamori's group works on applications-oriented research. His two laboratories at the University of Tokyo campus are used for more fundamental research. He spends the majority of his time at the campus, with one or two visits per week to KAST. The laboratory facilities at KAST include a well-equipped clean room for microfabrication and test labs; the WTEC panel ran short of time and couldn't visit the latter.

Recently, Prof. Kitamori founded the Institute of Microchemical Technology (IMT), a start-up company that is initially located on a separate floor of the same building at KAST. This company will market both the thermal lens microscope and microfluidic chips. The company has licensed patents belonging to KAST and is backed by both Kanagawa Prefecture and some private investors. The main purpose of the company is to facilitate technology transfer rather than to develop as a manufacturer. A goal for the company is to return profits to the prefecture to pay back some of its investment at KAST. Formation of the company required a significant amount of paperwork, according to Prof. Kitamori, due to his being affiliated with a national university. Five other companies have been spun out of KAST research groups recently.

Research Projects

Prof. Kitamori outlined his group's research themes in a very effective, animated presentation. His approach is to use standard microfabrication techniques to form microfluidic platforms, in which he does highly sophisticated, innovative chemistry. He sees a wide range of applications for integrated chemistry in the life sciences (e.g., disease diagnosis), environmental protection (e.g., water quality assurance), and combinatorial chemistry. The latter area is focused on chemical synthesis using the multiplexing capabilities of microflow systems. A major goal of his research is to extend the domain of integrated chemistry beyond the limitations of state-of-the-art capillary electrophoresis-based approaches, which are limited to aqueous solutions, ionic species, and fluorescence-based detection.

The substrate of choice is glass, with vertically stacked, interconnected chips being used for increasing the number of inputs and outputs. Much of his work is based on flow in channels that are 10-200 µm in diameter. However, his group is interested in the possibilities of "nanocapillaries" in which the behavior of water is unconventional. He hypothesizes that the water clusters are constrained by the capillary walls, resulting in different chemical behavior—such as a much longer decay constant for fluorescence. Surface tension fills the capillaries from the microchannels. In order to connect the microflow chips to conventional microtubing, very small, precisely machined reusable plastic connectors are used. A small local company machines these connectors for Prof. Kitamori's laboratory.

His first project is an integrated chemistry chip for cancer detection for detecting the marker "CEA." The assay uses coated microparticles that are held in place in the microchannel using a dam structure. Using a microfluidic chip, the assay time is reduced from 2-3 days to 30 minutes. A heavy metal (cobalt) analysis chip was also described for water quality testing.

Some of his group's most innovative work is the development of microfluidic structures to support micro unit operations and continuous flow chemical processing. The concept of unit operations is borrowed from macroscale synthetic chemistry. To implement micro diffusion mixers, guide structures have been etched into the microchannel in order to maintain the separation of flow streams. The guides are about 5 µm in height and are needed due to the very low flow velocity required to provide sufficient time for transport. By polymerizing at a flow interface between two streams, *in situ* fabrication of a nylon membrane was demonstrated. An example was described in which a substance was delivered in one phase, mixed with a second phase, and then extracted into a third phase. A particularly impressive demonstration was the co-axial flow of an air stream surrounded by fluid in a microchannel. Syringe pumps were used to drive the fluid through the microfluidic chips, with a pressure of several atmospheres at the inlets.

A second major contribution is the development of the thermal lens microscope (TLM) as a complement to fluorescence-based detection of molecules and its refinement to the point where it is capable of detecting on the order of 1-10 molecules. The work is motivated by the "small numbers problem" of integrated chemistry, which results from the need to detect nano-molar concentrations in femto-liter sample volumes. The physical basis for the TLM is that molecules emit heat to the surrounding fluid when they absorb optical energy. The result is a temperature profile in the fluid that causes a change in the refractive index and a transient optical lens. The change in focus can be detected using a confocal microscope at a different wavelength, thereby indirectly sensing the molecule of interest. The technique is non-specific, so the microfluidic system must be relied on to select the molecule of interest. Temperature sensitivities of 1 µK are needed to detect single molecules. Special lenses for the TLM are provided in the glass chip; these lenses are Selfoc™ optical communications components made by Nihon Sheet Glass.

The use of integrated chemistry chips for synthesis is also being pursued. Reaction rates are accelerated in the microscale; the rationale for this phenomenon is unclear. A stack of 10 glass chips with feedthroughs has been used to demonstrate the concept. The output of this micro chemical plant was substantial: on the order of 100 kg/year.

Laboratory Facilities

The KAST Integrated Chemistry clean room, rated at class 1000, was specially made by Hitachi, Ltd. The lab has very nice optical benches within the clean room. About 80% of the glass chips are fabricated in this laboratory. For the nanochannels, another laboratory at the University of Tokyo with e-beam lithography is used. A 50 fs pulse-width laser is used for time-resolved TLM.

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Uchiyama, K., *et al.* 2000. Thermal lens microscope. *Japan J. Appl. Phys*. 39:5316-5322.

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Date visited: 13 November, 2001

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BACKGROUND

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix C). A summary of the U.S. MEMS survey was provided to the Micromachine Center (Appendix C). Very brief reviews of the research at each of the U.S. panel members' institutions were presented (Appendix B).

MEMS has a long history in the United States and Japan; the WTEC panel was asked what we think about the Japanese MEMS research status. We believe that it is important enough for us to spend significant time analyzing Japanese MEMS activities. Likewise, Micromachine Center representatives see considerable excitement and energy in the U.S. MEMS community and are curious about activities in the United States.

ORGANIZATION AND OBJECTIVES OF THE MICROMACHINE CENTER

The Micromachine Center was established on 24 January, 1992, which coincided with the start of the national Micromachine Project. Total funding plan is approximately ¥25B. The Micromachine Center has a Board of Directors that supervises several committees: Administrative, Technical, Standardization, Cooperative Research, International, and Dissemination. The Secretariat is supervised by the Executive Director and has five departments: Administrative, Research, Information, International Exchange, and Planning. The Administrative Department provides overall coordination and support to member companies. The Research Department conducts R&D and standardization, manages R&D grants, and promotes the cooperation of multiple entities in research. The Information Department collects and distributes information, surveys and conducts research on basic technology, and edits a PR magazine. The International Exchange Department organizes the Micromachine Summit and International Seminars. The Planning Department performs promotion, symposium and exhibition organization, and the Micromachine picture contest for elementary school children.

The goal of the organization is to promote micromachine technology. Figure B.1 illustrates the overall philosophy of the national R&D project. The center conducts several activities:

- Generating research: through the National R&D Project (1990-2000), investigating basic technologies (e.g., high aspect ratio through-holes), reviewing future prospects, and determining R&D trends
- Collecting and providing information
- Coordinating exchange and cooperation: for example, the annual Micromachine Summit (the first one in March, 1995; in 2002, the summit in the Netherlands includes Prof. Muller and J. Giachino) and the

annual International Micromachine Symposium (instituted in November 2000). Currently, a chief U.S. delegate to the Micromachine Summit is being sought as Prof. Al Pisano from U.C., Berkeley, is stepping down as the existing U.S. chief delegate.

- Providing university grants: ¥3M/2 years
- Promoting standardization: through studying what needs to be standardized via committees (e.g., MMC TR(S001) in October 1998 and MMC TR(S002) in June 2000). The joint committees come from the center, the universities, and industries. TR(S001) is available at http://www.iijnet.or.jp/MMC/. For example, thin-film testing methods are now being studied with support from the New Energy and Technology Development Organization (NEDO). Studying the need for standardization has been a three-year exercise. In 2002, work will begin to propose standards. A web forum has also been organized (including Michael Gaitan from NIST). An international forum is being planned in Tokyo during 2002.
- Promotion: for example, the Micromachine Exhibition (11th annual in November 2000 in Tokyo). This includes some activities with elementary school children to encourage them to attend engineering school. The Micromachine Center representatives were concerned about increasingly lower interest in engineering in Japan. In Japan, approximately 25-30% of entry-level college students plan to study engineering. In the United States, this is now to 5-10%. Japanese students, like American students, are becoming too busy (e.g., playing video games at a rapid pace), so there is less time to ponder, to be creative, and to think. The picture shown in Figure B.2 shows several recent entries into the Micromachine Picture Contest. This is the 7th annual contest and asks children to envision the use of new technology. The top four students receive prizes, like Olympus cameras, electronic dictionaries, etc. Each year, there are approximately 2000 pictures entered. Entries come from local schools and member companies. The goal is to encourage school children to think about the technology as being more than a "black box."

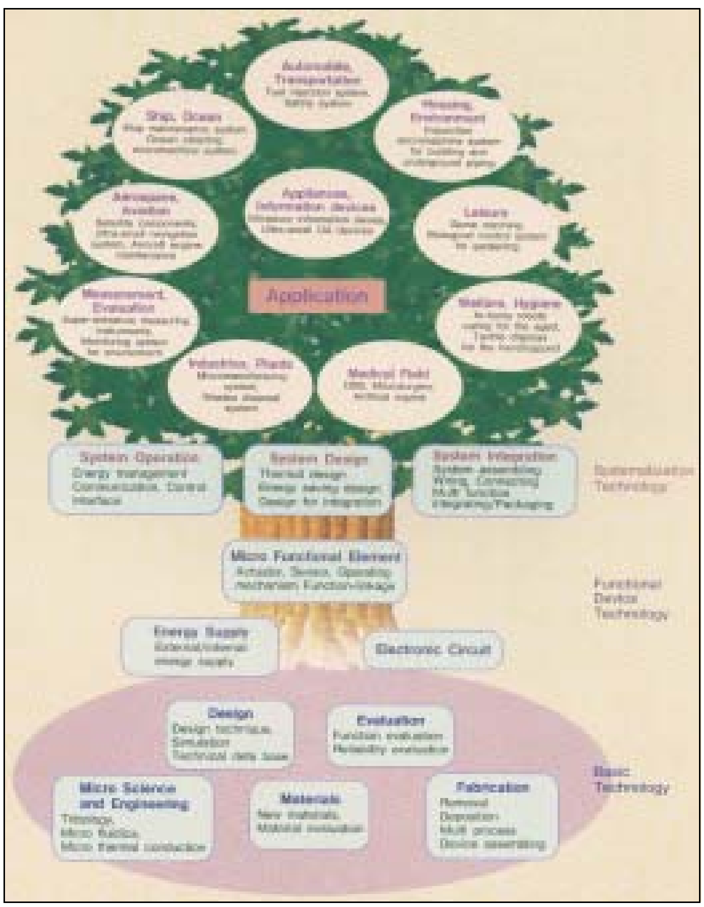

Figure B.1. The chart illustrating the overall philosophy and goals of the national R&D project.

Figure B.2. Several examples of recent entries into the Micromachine Picture Contest.

The Micromachine Center has 33 member companies. These companies are mainly Japanese, but a U.S. and an Australian university are also members.

R&D ACTIVITIES AT THE MICROMACHINE CENTER

The Japanese define a “micromachine” as an extremely small machine, including milli- through nano-technologies. This definition is significantly broader than the Micro-Electromechanical Systems (MEMS) definition that is common in the United States and, even, the Microsystem Technology (MST) definition that is common in Europe. MEMS researchers started from microelectronics, whereas micromachine researchers started from a mechatronics background. The scope of the micromachine is much wider than MEMS or MST.

In the early 1990s, the Japanese economy was booming so its science and technology shifted to more basic and original projects, like micromachining. For example, “micronization” has occurred in biotechnology, materials, electronics (e.g., sensor array), and mechanics (e.g., the microcar). In the late 1980s, micronization was becoming more necessary.

Therefore, the Micromachine Project was initiated in 1991. Two phases were planned, each five years in length. During the first phase, “conceptual” systems were explored. These were the only proposed areas of study. The key domains were as follows:

1. Advance maintenance systems for power plants (Figure B.3)

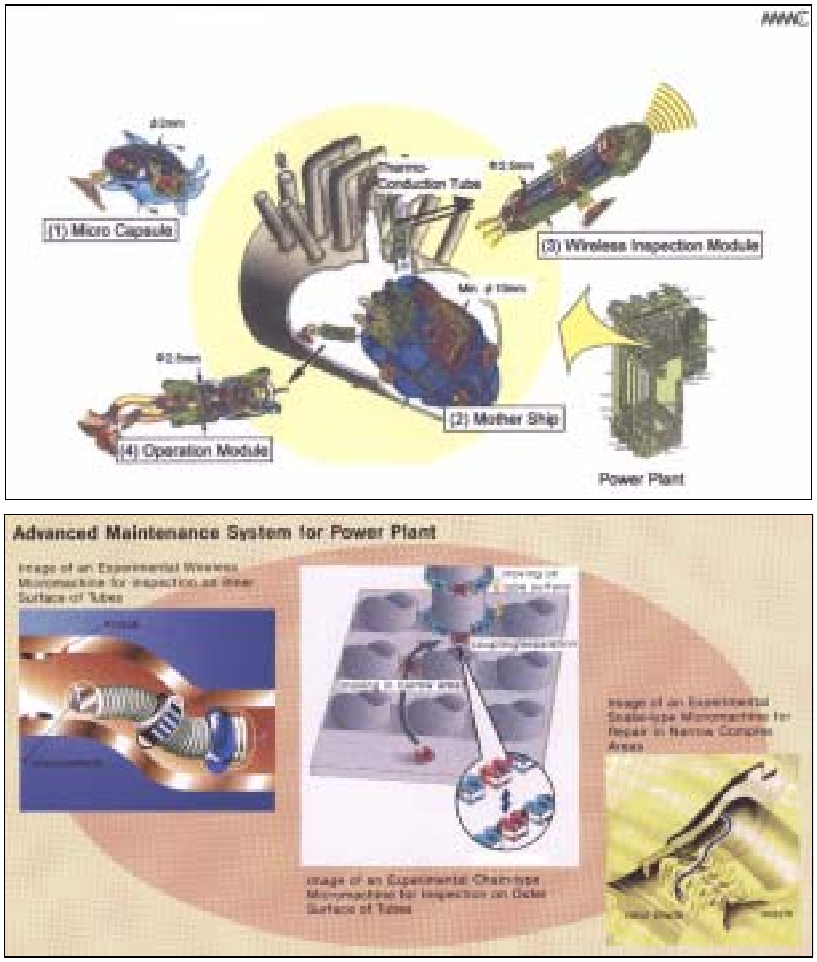

Figure B.3. Advanced maintenance system for power plant.

2. Microfactory systems

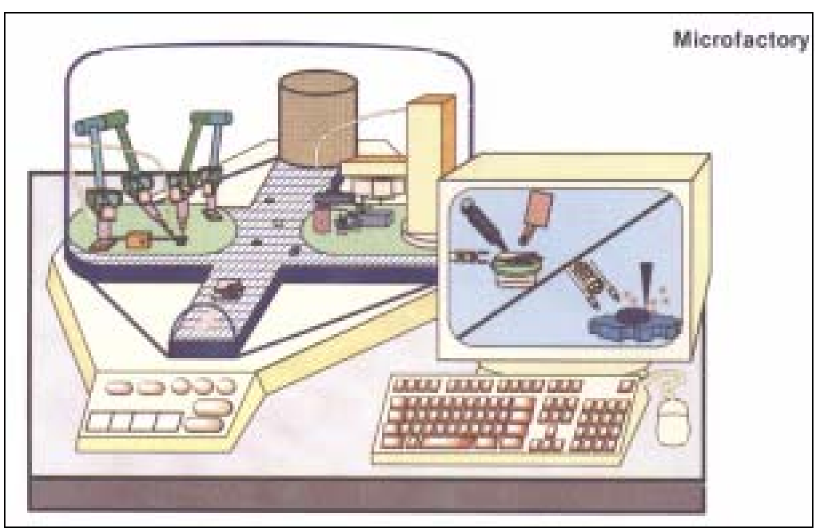

Figure B.4. Microfactory system.

3. Intraluminal diagnostic & therapeutic system—the budget for this area was inadequate, so only the elemental technologies were funded. System development was not funded.

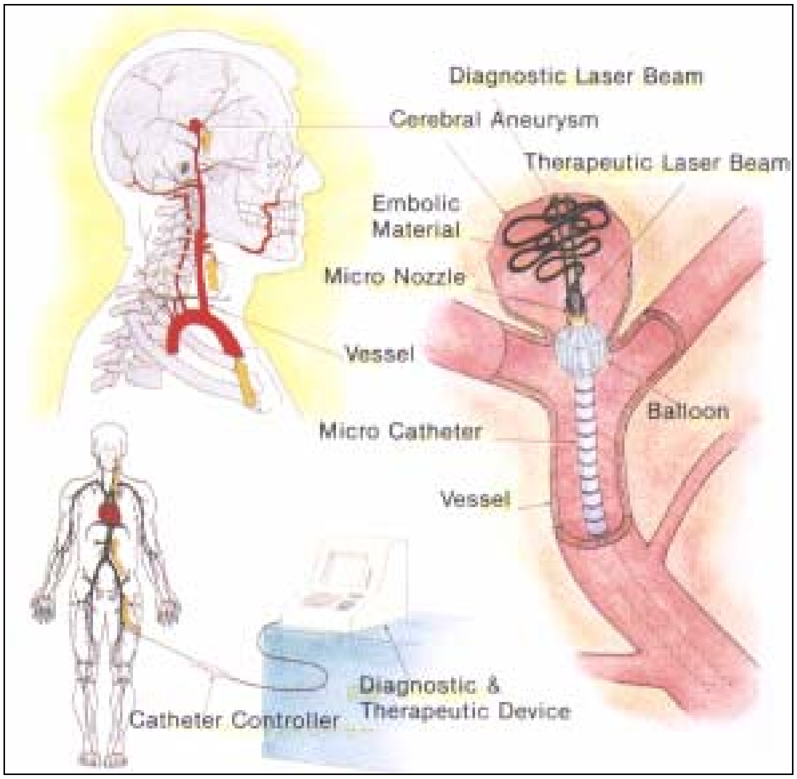

Figure B.5. Intraluminal diagnostic and therapeutic system

The second phase included system technologies for development. The goal was to develop system technology for micromachines. For example, a wireless micromachine, a chain-type micromachine (for outer pipe inspection), a catheter-type micromachine, and a microfactory were used as test beds for research.

The wireless micromachine, included a CCD camera, an electrostatic actuated focusing mechanism (like an inchworm), a microwave-based energy supply and data transmission, and a piezoelectric driving actuator. The power supply (wireless) and heat generation from the piezoelectric were the two most difficult problems to solve. In addition, communication in a harsh environment was also difficult.

The inspection for the outer surface of the tubes, small machines follow the outside of the tubes. A linked group of 10 micromachines is used. These self-assemble to form a chain. This includes a micro-reducer gear assembly and microgyroscopes.

The catheter-type micromachine was described as easy because it was wireline. This was developed as a microwelding device.

The microfactory was developed. It included an optically (laser) activated bubble pump. The laser activates a phase change in the fluid channel. It enables the small, remote assembly of devices—ideally, while devices are in (traditional) inventory sites (e.g., during shipment).

Several industrial partners were involved in this development.

Finally, an ultrasonic signal-emitting device was described using high aspect ratio MEMS-like technology in ceramic. Sumitomo Electric is commercializing this.

A video of the Micromachine Center was presented.

Over 580 patents have been applied for within Japan. The patents tend to be co-owned by the company and the NEDO. The patents are supposed to be open for third party use because these were paid for with public funds.

SUMMARY AND FUTURE FOCUS OF THE MICROMACHINE CENTER

The most significant outcome from the MITI Micromachine Project is the paradigm of key technologies described above. These technologies will be disseminated to a variety of potential customers. Some future efforts will be aimed at new applications for these key technologies. Additionally, emphasis in nanotechnology will begin in a “top-down” (big to small) approach. MMC will continue to bridge existing and potential technologies. MMC now has to look for specific applications. Microfluidics is one of these specific applications; the others are IT and environmental applications. Third, to move on more precise and nano area, triggered by President Clinton’s National Nanotechnology Initiative (NNI), which triggered Japanese interest and discussion. In these discussions, micromachining was a major focus because moving into the nano area through micromachines was top-down and current nano technology is a bottom-up approach.

Questions and Answers:

Question: Will the Micromachine Center play a role in nanotechnology and/or will there be collaboration with other organizations? What will the Micromachine Center’s role be in the next 10 years?

Answer: No specific strategy has been set. The inclusion of nanotechnology and microfluidics are being considered, but a final strategy has not been developed. The future role for the Micromachine Center will, however, continue to be to bridge the industrial and scientific communities. Funding for this effort will come primarily from public sources if the effort is to be successful.

Question: What lessons have been learned from the 10-year program?

Answer: The program ended successfully with a lot of outcomes, while a new paradigm of micromachine is recognized as more sophisticated and takes more time to complete than expected. In management we learned the R&D environment in industry has changed dramatically, focusing on more short-term goals. Ten years ago, much more industrial funding was available because the economic conditions were more prosperous. There is some concern that the more short-term focus in industry will diminish the investment in long-term research efforts like the Micromachine Center. There needs to be much greater focus on long-term research. Also, ten years ago, many international communities envied the original Micromachine Project.

Question: How is the international interaction?

Answer: In the mid-1980s, there was a much greater nationalistic focus on technologies. Today, companies are much more international. Therefore, the Micromachine Center would welcome interactions with U.S. companies and organizations, but there does not appear to be a direct counterpart to the center in the United States. In Europe, organizations like Nexus are more closely parallel. Membership in the Micromachine Center is open internationally for ¥300,000/year. For example, SRI International (U.S.) is a member.

Question: Who interfaces with the schools for the drawing contest? Is it through the teachers and MMC?

Answer: Every year the MMC collected about 2000 pictures drawn by children. The member companies have constant contact with nearby schools, and they are the ones who contact the schools. MMC did not have any direct contact with schools at the beginning but just sent materials, and then the teachers managed the contest. Now MMC has a list of schools interested in the program. They have not tracked students to see where the students go, and the first generation after eight years should be entering college this year. The idea of the drawing contest is to offer opportunities, not to collect ideas.

Question: Who selected the original projects, and why did you choose these areas?

Answer: Authorities picked technologies proposed by researchers based on their budget. Power plants need small machines to detect defaults on narrow pipes, gases, etc. and so this was a key application domain. Other areas included medical applications (but for the medical area the budget was not adequate, and so only work on elemental technologies was done, not on systems). The last was a microfactory for energy and space saving.

Question: What was the largest problem as you developed these?

Answer: There were many obstacles to overcome, especially energy supply and also heat and how to get rid of the heat.

Question: Have you looked at using inductors to conserve the energy to reuse the energy so you do not dissipate it?

Answer: In this project we did not look at this and just dispersed the heat. In this phase the most important thing was how to integrate the device into a small space and how to communicate without wire. These devices need a lot of energy and a long time to solve the problem of managing energy was needed.

Question: What do you see your role in the next 10 years?

Answer: There is no good answer. We should do something; it is a common feeling, but we have no specific approach. Everyone recognizes there should be key research technologies between the micro and nano sciences and the research should be diffused by two approaches. The future role may be bridging between industry and the scientific society.

Question: Who will fund this future effort?

Answer: We should look for public funds for this.

Question: How has the economy affected funding?

Answer: Ten years ago companies were generous, and researchers could take long term research, but now the companies' target is more near future, and long-term research is more difficult. This is a very dramatic change, and we are lucky that we started 10 years ago.

Question: Will you get industrial funding, but less now? Do you expect less of your money to come from industrial projects?

Answer: It depends on the project. Companies want to develop immediate products. The pendulum is swinging.

Question: The first five years were exploring basic technologies, and next five years were to develop systems with applications. What do you tell people you will do for the next five years?

Answer: We do not have extreme conditions like the United States in defense applications. The project was started for 10 years. At the beginning there was only a five-year plan. At the end of five years we evaluated key technologies. The final target was to develop technologies to make machines, so system technologies was the second phase. Maintenance application for power plants was the one system where they want to have micromachines in the future that those who were surveyed selected. The main purpose was not to develop the application itself. We have developed many key fundamental technologies. Our efforts will be focused on commercialization.

Question: Do you see a potential for future collaboration with U.S. industry and universities?

Answer: MMC could not find an appropriate counterpart. In Europe, there are counterparts like Nexus, etc. It is hard to find a similar organization in the United States. It is difficult to communicate with each professor's group. MMC welcomes foreign members. Since April they have been opened to new membership, and members get information. Annual fees are ¥300000/year, and the members get reports, and also they have a Japanese database. The only U.S. member is SRI. MMC used to have IS Robotics and Prof. Brooks, but they are not members anymore.

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BACKGROUND

Murata Manufacturing Company, Ltd. was established in 1944 and incorporated in 1950. Murata produces and manufactures ceramic materials and electronic devices made from the ceramic materials. It currently has over 50 subsidiaries, and FY2000 employees and sales (including subsidiaries) of over 27,500 people and ¥584,000M, respectively. The company is organized into a number of divisions, including three components divisions, a device products division, a circuit module products division, a sales and marketing division, and a research and development division.

Murata’s main products focus on exploiting the dielectric, piezoelectric, magnetic, pyroelectric, and/or semiconducting properties of ceramic materials. Examples of devices in these categories include ceramic chip capacitors, EMI suppression filters, and microwave filters; ceramic resonators and piezoelectric buzzers; ferrite-based EMI suppression; pyroelectric infrared sensors; and thermistors. These devices find use in such systems as cellular telephones, PCs and displays, VCRs, and televisions.

The philosophy of the company is to emphasize vertical integration from raw materials up through production systems. Unlike many corporations that outsource key elements of their business such as raw materials or packaging, Murata has elected to maintain control throughout the supply chain by internalizing the key elements of production. Murata employs approximately 2,000 engineers, and they are divided roughly by thirds into the areas of materials engineering, mechanical engineering, and component design.

Murata has benefited tremendously from the surge in cellular and other wireless markets. Although the selling price of many of these components is low, the volumes are high. For example, Murata claims the use of approximately 190 chip monolithic ceramic capacitors in a cellular telephone application and a global market share of 45% of chip monolithic ceramic capacitors. Sales of capacitors accounted for approximately ¥250,000M (approximately U.S. $2 billion) in 2000.

Group Overview

The Research and Development Division of the Murata Manufacturing Company is organized into three groups: Group II, primarily concerned with raw material technology; Group III, primarily concerned with application circuitry; and Group IV, primarily concerned with thin films, opto-ceramics, and new materials.

Total R&D expenditure per year is approximately ¥30,000M, or approximately $250 million. This expenditure ranges between 5% and 7% of sales.

Murata's main R&D focus is clearly on exploiting and extending dominance in the ceramics arenas. Targeted areas include the following:

1. Microwave semiconductor technology, consisting of active components (e.g., GaAs) that are integrable with ceramic components to form high performance systems with application to satellite broadcasting, mobile telecommunications, and other telecommunication technologies. The investment in GaAs fabrication technology is another example of the vertical integration philosophy of the company.
2. Millimeter-wave components and module technologies, again exploiting ceramics expertise, for developments in broadband communication (i.e., anticipation of the continual increase in communications frequencies) and millimeter-wave radar for vehicle safety. Examples of such components include millimeter-wave dielectric filters.
3. Ceramic multilayer module technologies, continuing to push the state-of-the-art in co-fired ceramic technology, with functionality such as passive elements (R, L, C) fabricated directly within the volume of the ceramic package;
4. BGS wave devices that exploit unique ceramic properties to create new microwave devices.

MEMS R&D ACTIVITIES

The interest of the WTEC panel was to determine the extent of Murata's MEMS activities. Although MEMS appeared to be a relatively small effort compared with the major R&D activities discussed above, activity in the MEMS area was moderate. Surprisingly, much of the MEMS activity was directed at sensors and actuators, rather than RF MEMS. However, some of the questions during the U.S. MEMS overview presentation indicated interest in the RF MEMS area, especially in the subareas of antennas and resonators.

MEMS activities in Murata began in 1990 with installation of equipment. Since then, research has progressed in three phases: development of specific fabrication technologies (1992-1994); fabrication of gyros, accelerometers, and some basic devices (1995-1997); and focusing on gyro applications with a beginning survey on RF MEMS (1998-2001). Major technologies utilized include anisotropic wet etching of silicon (especially (110) material); dry etching/deep reactive ion etching; and electroplating. Building on some of the core strengths of Murata, packaging research appears to be a priority, with emphasis on vacuum packaging approaches for MEMS.

Three specific MEMS projects were discussed, all of which were related to gyroscopic-based sensing and tied to the Japanese national MITI project. Published papers were given to the group and are listed in the references.

The first device is a bulk micromachined gyro from single-crystal silicon. A double-frame design is utilized in order to improve performance. An interesting packaging scheme using vertical through-holes sandblasted through anodically-bondable glass to form both a vacuum seal and electrical feedthroughs was employed. A resilient organic mask is utilized during this process, and it takes 10-15 minutes to sandblast via holes through 500 microns of anodically-bondable Pyrex. The device is not integrated with electronics and has a packaged size smaller than 5x5 mm. The noise-equivalent angular rate is currently 0.3 degree/second in a 40 Hz bandwidth, and Murata is currently on the third or fourth generation device. When asked about commercialization, the response was that they 'want to commercialize' this device, but are thinking about what the best field is. They are currently considering automotive applications, since the camcorder stabilization application cost structure may be unable to support it.

The second device discussed was a gyroscope fabricated as a position sensor for the MITI machine inspection catheter. The structure itself was relatively simple, similar in design to the first gyro but using only a single-frame approach. A similar packaging technology was also utilized, with the addition of a non-evaporative getter incorporated into the vacuum package. This device achieved a sensitivity of

14 mV/(deg/sec) with a dynamic range of 90 deg/s; and a noise-equivalent angular rate of 0.057 deg/s in a 10 Hz bandwidth.

The final device was a further refined gyroscope that utilized 'motion adjustment technology' (i.e., utilize multiple bias electrodes surrounding the main electrode to adjust the trajectory of the mass movement, thereby reducing the non-ideal movements that would be caused by fabrication non-idealities). Typically without adjustment, non-ideal excursions on the order of 0.1 micron were observed; utilizing this technology, such excursions seem to be completely suppressed on this scale. Noise is greatly reduced from previous designs, although sensitivity is not changed much (as expected). This device achieved a noise-equivalent angular rate of 0.013 deg/s in a 10 Hz bandwidth.

PARADIGM SHIFTS AND OUTLOOK

Murata's MEMS R&D effort has been influenced strongly by the Japanese national MITI initiative in the past, with a strong focus on gyro applications. Now the MITI project has ended, and the equipment base and local MEMS expertise are ready to turn to new applications. Future plans include adaptation of the gyro efforts for automotive application (e.g., measurement of rollover and yaw rate) as well as other applications (e.g., as input devices and motion monitors). In addition, Murata is interested in hybridizing mechanical sensors, using the packaging technology to create multisensor platforms such as gyroscopes plus accelerometers within the same package. Finally, and perhaps most significantly, they are beginning to turn their attention to RF components and mentioned RF switches, inductors, and tunable capacitors as areas of future interest. Other interest areas mentioned included 5.2 GHz wireless LAN; RF LC filters implemented in multilayer co-fired ceramic technology; and dielectric antennas.

The overall philosophy appears to be that Murata is currently a components company and would like to become a manufacturer and supplier of MEMS components to build on this core strength. They would like to keep their focus on bulk micromachining, and on applications where only components, not IC systems, are required. They are not afraid of component assembly (e.g., MEMS components plus silicon or GaAs chips assembled onto a board) to create complex and miniature MEMS systems; instead, they point to the commercially successful current approach of assembling chip capacitors and chips onto boards, even in very high volume markets such as wireless handheld products, as proof that assembly of MEMS components into systems is viable.

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BACKGROUND

Hosts at Olympus first provided an overview of activities followed by a detailed description of a few of the projects, and a demonstration of some of the projects developed as a result of the Micromachine Project. A review of the WTEC objectives was then presented, including the purpose and timing of the study (Appendix C). A summary of the U.S. MEMS survey was provided to the Micromachine Center (Appendix C). Very brief reviews of the research at each of the U.S. panel members' institutions were presented (Appendix B).

REVIEW OF MEMS ACTIVITIES AT OLYMPUS

The hosts all belong to the Corporate R&D Center where most of the research in MEMS and micromachines is carried out. Olympus is one of the original member companies belonging to the Micromachine Center and was involved from 1991 until spring 2001 in the development of micromachines for a variety of applications (see Figure B.6). The main goal of their micromachine projects was establishing the elemental technology for realizing a micromachine that can work in restricted areas, for example, the inspection/repair of a complicated machine system, diagnosis and treatment within the human body, and the miniaturization of manufacturing equipment. Olympus' core applications and developments during the past decade occurred in several fields including the following:

- Medical Field: endoscopes, catheters, tactile sensors, and chips for DNA testing
- Industrial Field: catheters for repair, microfactory, and microsensors

- Imaging and Information Field: magneto-optical recording, scanners, and inkjet print heads.
- Basic technologies:
  - Si micro-fabrication technology
  - Micro-assembly technology
  - Micro-optics technology
  - Microfluidics

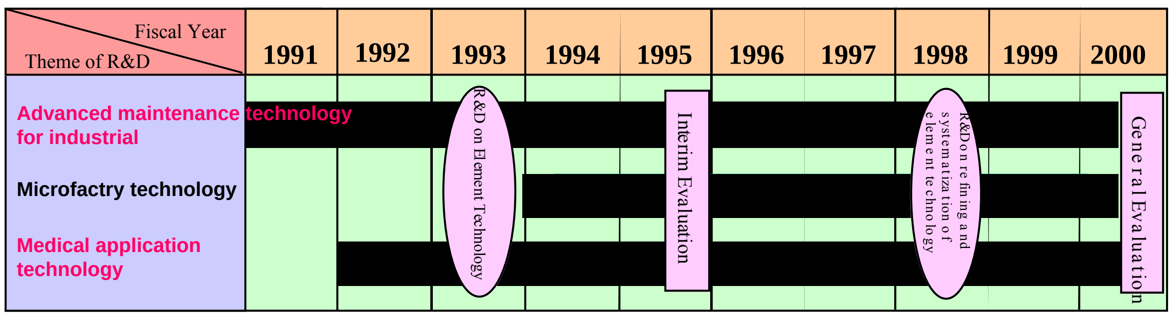


Figure B.6. Timeline showing Olympus activities under the MITI's Micromachines Project

Olympus' view of micromachines and the features they provide include the following:

1. Working in tight, complicated areas, e.g., minimally invasive diagnosis & treatment and thinner, more sophisticated endoscopes
2. Enhanced portability, e.g., smaller information systems
3. Micron-level control, e.g., cell or DNA manipulation

Several presentations reviewed projects in the fields mentioned above. These are briefly reviewed here.

Medical Field

Endoscopes and Catheters

Endoscopes have been developed for several medical applications. Endoscopes need several devices to operate them in tight and complex regions of the body. They need actuators for manipulation and control, sensors for navigation and measurement of important parameters, and devices for the repair of damaged parts. The concept of an endoscope/cather device is shown in Figure B.7. Two different catheters have been developed. The first one shown in Figure B.8 is a microfine active bending catheter that includes a contact sensor to minimize or avoid contact with the vessel as it is inserted through it. It includes a light/vision device. The second catheter is shown in Figure B.9, where a piezoelectric tactile sensor is incorporated that can sense the difference between soft and hard tissues. The operation of these devices was demonstrated.

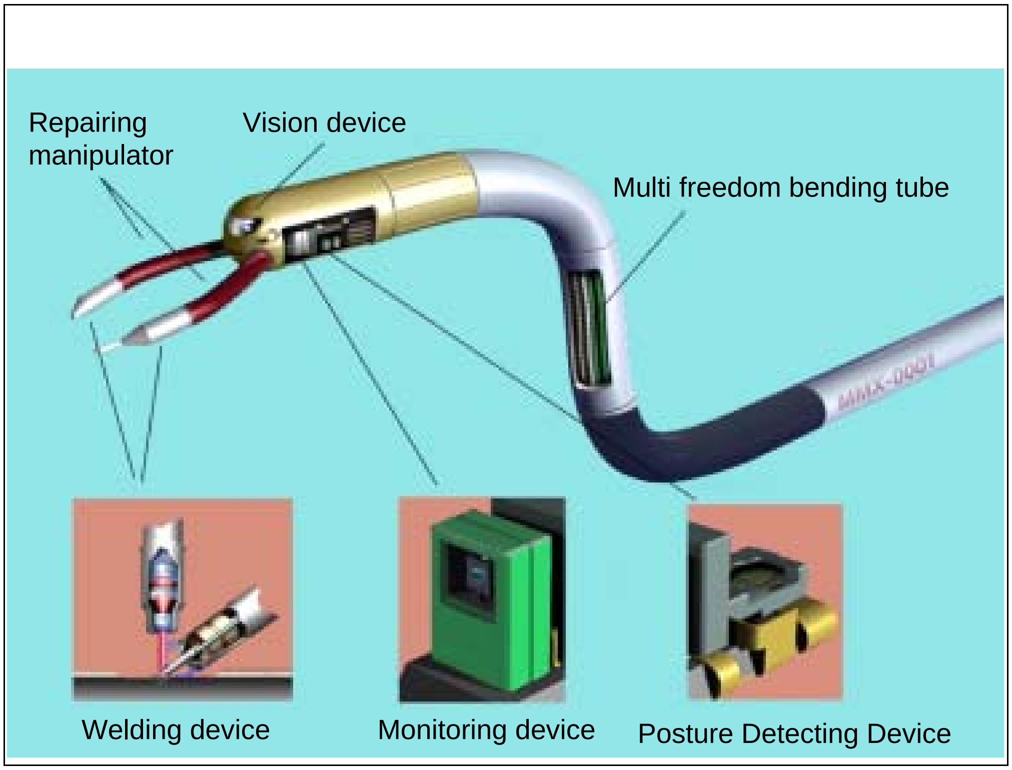
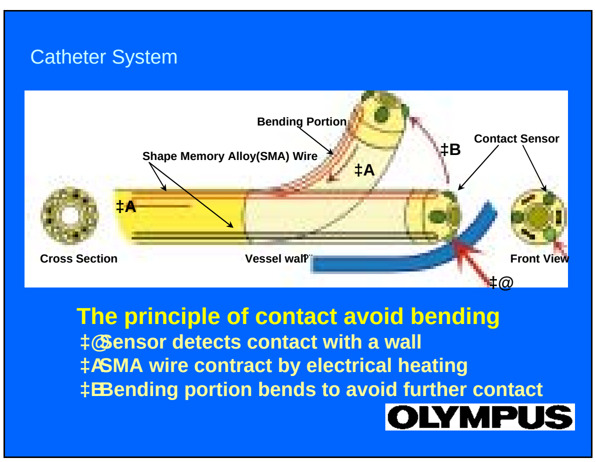


Figure B.7. Conceptual drawing of an endoscope for medical and industrial applications.



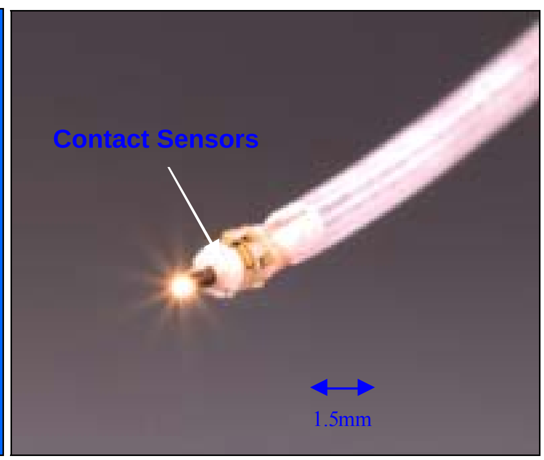


Figure B.8. A microfine active bending catheter for medical applications.

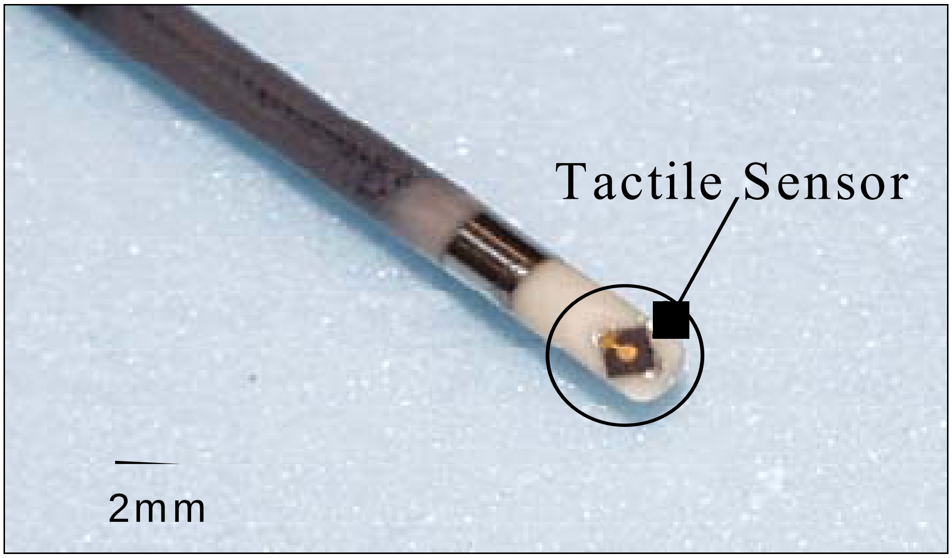


Figure B.9. A catheter with a piezoelectric force sensor at the tip.

DNA Analysis and Proteomics:

In addition to catheters, Olympus has developed bio-chips for DNA and chemical testing and analysis. The chip developed by Olympus is based on free-flow electrophoresis that is used for rapid sample preparation. The concept for this device is shown in Figure B.10. It uses two Pyrex glass wafers that are bonded together. Inlet holes allow the introduction of a sample into the gap (30µm high) formed between the two glass plates, while outlet holes are formed in a linear fashion at the other end of the wafer stack. Two electrodes are placed orthogonally to the path of fluid flow, and when a voltage is applied, the components of a sample are separated through electrophoresis and exit through the outlet holes. Electro-osmotic control of fluid flow is shown in Figure B.11.

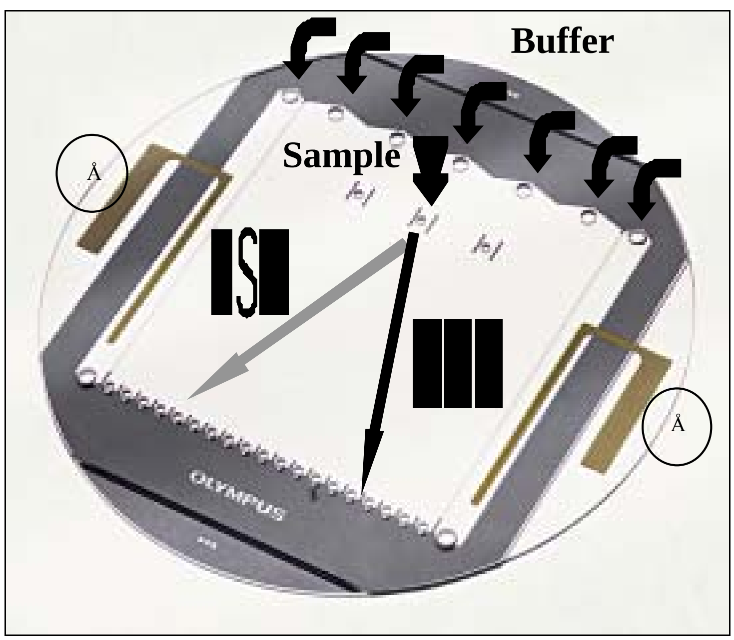


Figure B.10. Structure of Free-Flow Electrophoresis (FFE) module. The size of the whole chip is 100x2(H) mm, while the separation bed is 48(W)x40.5(L)x0.03(D) mm.

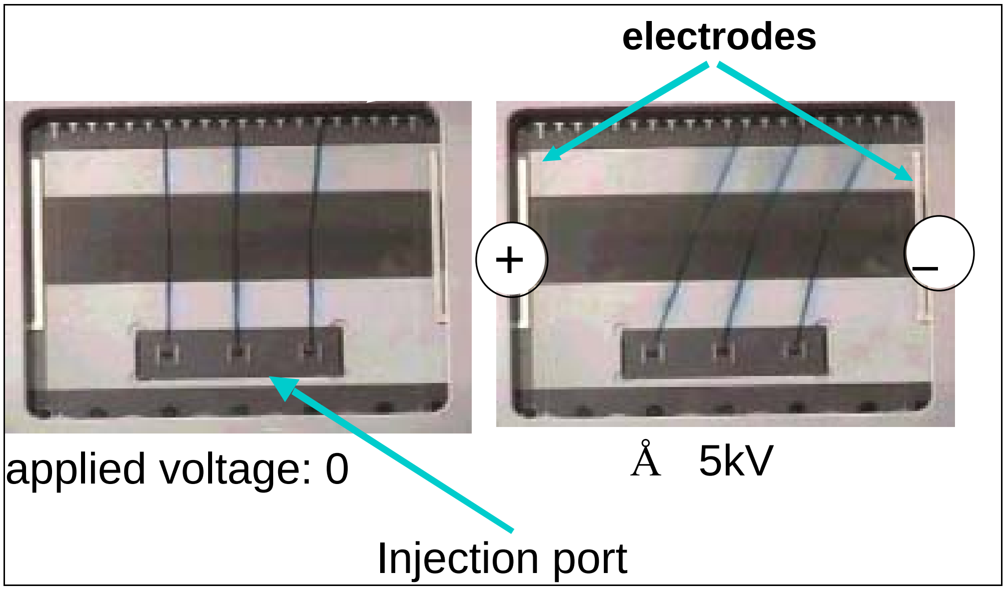


Figure B.11 Demonstration of electro-osmotic flow in the FFE cell.

After samples were collected from each outlet, the solutions were analyzed by 1% agarose gel electrophoresis. This technology was first developed for DNA applications, but now the emphasis of the company is to apply it in the field of proteomics. The technology has also been used to separate different dyes.

Industrial Field

Endoscopes and Catheters

The technologies and devices developed for medical catheters, shown above, can also be used in the industrial field for repairing damaged pipes. A laser-welding catheter has been developed that can weld cracks in pipes *in situ*. The laser used is a YAG laser and provides a power of over 70W over a 0.5 mm depth. Pneumatic actuators are used to move the tip of the catheter around as it is inserted into the pipe of interest.

Optical MEMS and Scanners

One of the most important applications of MEMS and micromachines is in scanners and optical switching systems. Olympus is especially interested in this area because scanners are at the heart of many instruments and microscopic inspection systems that it sells. Olympus has developed several different scanners for application in different areas. In one application, a larger mirror (2.5x2 mm) has been developed with MEMS technology that utilizes electromagnetic actuation and has a resonant frequency of 100Hz. This device uses polyimide hinges since polyimide can withstand shock in the range of 2000G better than silicon.

Because of its low frequency, a second scanner has also been developed with a lower frequency. This scanner is also based on electromagnetic actuation but uses silicon hinges. It has a resonant frequency of 4kHz, is 4.5x3.3 mm, and can withstand a shock in the range of 100G. It has been successfully tested for more than 10E11 cycles.

The second scanner is used in a laser scanning microscope that Olympus makes (OLS 1100). The use of the micromachined device has been critical to improving the overall performance of the microscope since it achieved less power consumption, has better scan angle stability, and is more reliable. This is the first product (of all of the above-mentioned projects) that is commercially produced and using micromachines. Another product is an AFM system that also uses some micromachined cantilevers.

In addition to the above devices, Olympus is developing a sub-mm size scanner that was originally aimed at a compact size optical system. The scanner uses electrostatic actuation, is about 0.5 mm in size, and provides 2-D scanning capability. The technology used is based on SOI and bulk micromachining and is applicable on optical switching systems with little change as well.

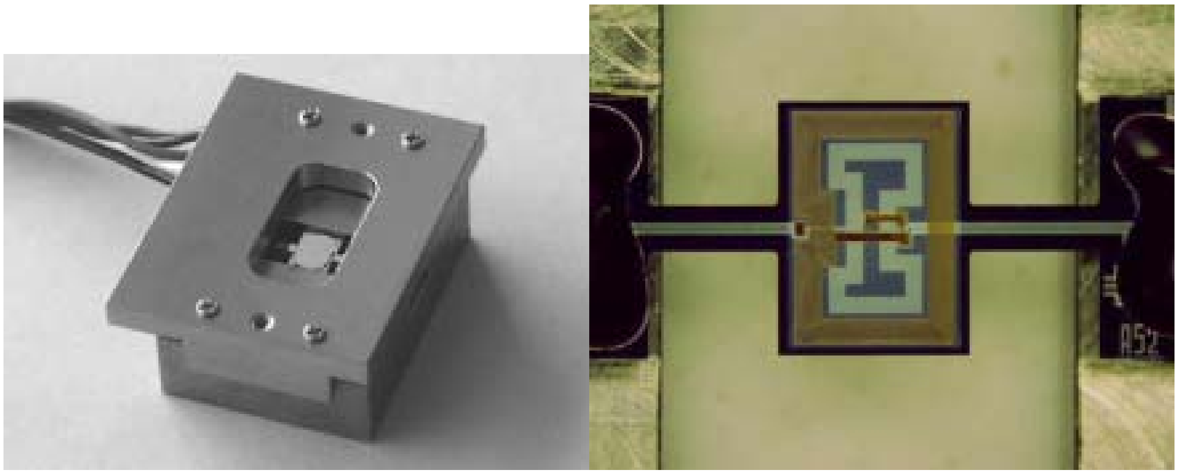


Figure B.12. Electromagnetic MEMS scanner for a laser scanning microscope (OLS1100)

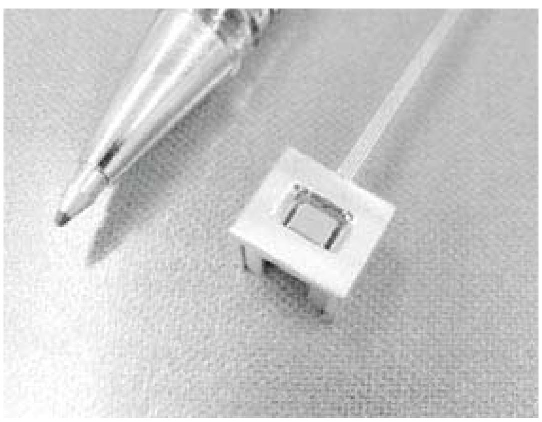


Figure B.13. Polyimide hinge electromagnetic scanner.

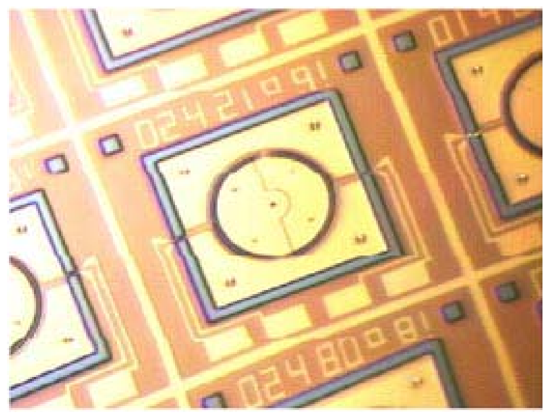


Figure B.14. Sub-mm size electrostatic gimbal scanner

Papers based on these devices have been presented at various conferences.

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OLYMPUS MEMS FOUNDRY SERVICES

One of the most important announcements made by Olympus was that it is now offering fabrication services through its MEMS foundry. This was first announced at the Micromachine Exhibition 2001, Tokyo, Oct. 30-Nov. 2, 2001. This MEMS foundry can be used for services ranging from prototyping to volume production. It will provide customers with the best solution based on Olympus' rich experiences obtained through the past 10 years.

The foundry provides design service, prototyping service, and production by certified lines.

These services are supported by precision, optical, and bio technologies in OLYMPUS. One of the important features of Olympus' foundry service is that MEMS can be mixed with CMOS and BiCMOS. The foundry has about 10 engineers.

The following technological capabilities are provided through the Olympus MEMS foundry:

- 4-inch wafer
- Projection aligner with deep depth of focus
- I-line stepper
- Double sided aligner
- Thin film deposition and electro-plating
- Dry etching—including DRIE
- Wet etching
- Wafer bonding
- Test and packaging

The main motivation for providing this foundry service was that the fabrication facility had excess capacity, and the company feels that it can utilize this excess capacity to provide services, generate revenues, and therefore sustain the operation of the facility. They expect this activity to bring them new seeds of technology and comprehensive collaboration with universities and other companies.

QUESTIONS AND ANSWERS

Question: Does Olympus have any plans to work on RF MEMS?

Answer: There are no plans at this moment to work on RF MEMS. Olympus has concentrated on optical and biomedical MEMS.

Question: Does the end of the Micromachine Project mean that Olympus will not receive any additional funding and will end its activities here?

Answer: No, although the amount of funding has been reduced, small projects are still funded and will continue.

Question: What do you think are the areas that need additional support in Japan to further improve the state of MEMS?

Answer: The main weakness is that universities do not have very good fabrication facilities and are not very active. This means that MEMS engineers who are well trained are not yet easily available.

Question: What can you do to fix this problem?

Answer: We need more foundries so students can use these services, and more university research groups to provide the ideas and seeds for future technologies that industry can use to develop future products.

Question: Will you provide your services to universities, maybe for free?

Answer: Because of the cost involved in operating fabrication facilities, it is generally not economical to provide foundry services to universities at low cost. However, this will be done if there is a common interest or collaboration between the company and a specific university.

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OMRON COMPANY/DIVISION OVERVIEW

Omron has five virtual companies and a central Business Development Head Office. The business units are the Electronic Components Company (ECB), the Industrial Automation Company, the Social Systems Company, the Healthcare Company, and the Creative Service Company.

Within the ECB are Strategic Planning, Electronic & Mechanical Components (EMC: e.g., switch, relay, and connectors), Automotive Electronic Components (e.g., power switch, ABS, EVS), the Semiconductor Division, Office Automation (e.g., paper sorting), and the Amusement Component Division, among others.

The ECB core technologies include: precision assembly, sensing technology, micromachine technology, semiconductor technology (ultra low pressure sensor), wireless communication technology (pulse radar for near field), and new material technology.

Within the Semiconductor Division, there are approximately 250 people. The sales budget is about $100M. The division contains two large departments: the Silicon Device group and the Microlens business group. The factory is located in Minakuchi for fabrication. Assembly is outsourced.

The major products in the Silicon Device group include pressure sensors, accelerometers, and analog custom ICs. Production of these devices started in the 1980s. The main applications are for blood pressure and factory automation. The Microlens group has P-MLA (e.g., projector) and B-MLA (e.g., backlight for Casio PDAs) and cell phones (e.g., for Samsung, etc.). Sales are approximately $30M/yr.

The long-term scheme for silicon devices is to be the Number One custom analog supplier in Japan and a major MEMS supplier and foundry in the world. The strategy is as follows:

1. To acquire BiCMOS and CMOS process and production capability. Currently, Omron only has high voltage (10-40 V) bipolar capability.
2. To improve, expand, and acquire analog design capability.
3. To develop and acquire surface micromachining technology. Currently, Omron has only bulk micromachining technology, but they would also like to acquire surface micromachining technology.

Omron executives believe this can happen in a variety of ways and are not limiting themselves to doing this internally.

Current capabilities include bipolar processing with > 3 µm, IC packaging, custom IC, and marketing to industrial applications with bulk micromachining. By 2003, they would like to also have BiCMOS and CMOS capability at about 1.5 µm and 15 V, modules packaging for sensor drivers, and application-specified standard products for consumer markets with surface micromachining. By 2005, they are interested in CMOS integrated surface micromachining (they are not interested in bipolar integration of micromachining).

The Semiconductor Division contributes 6% of the entire company sales. EMC is 54%. Approximately 57% of the sales are in Japan and 20% in North America. Five years ago, more than 60% of their sales were in Japan and the rest of Asia was less than 10%. This is now changing as growth in the rest of Asia (especially China) has developed. Not much change has occurred in North America; there have been sales in the United States for more than two decades. Over 70% of the sales in ECB is relays and switches. Omron has a greater than 10% market share in this area. In the United States, this is in automotive relays. Two factories are located in North America: in Canada and in Schaumburg, Illinois.

The Omron Semiconductor Division includes the MEMS development group that is located in the same building as the Minakuchi factory, approximately 30 miles from Kyoto. The factory was founded in April 1975 and employs approximately 230 people. The MEMS and bipolar clean rooms are kept separate.

WTEC PRESENTATION

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix C). A summary of the U.S. MEMS survey was provided to the Micromachine Center (Appendix C). Very brief reviews of the research at each of the U.S. panel members were presented (Appendix B).

OMRON MEMS PRODUCT TECHNOLOGY OVERVIEW

The MEMS activity in Omron is done in two locations: in ECB, the Semiconductor Division is the profit center and provides development and productization of technology. The Central R&D Laboratory is developing new MEMS technologies (e.g., the micromachined relay: MMR).

The business domain is focused on industrial, medical, and automotive for pressure sensing and acceleration sensing. Future product interests are motion sensors, RF MEMS, DNA chip/microTAS, etc. for game applications, IT, and the biology markets. Competition is from ADI in the Nintendo Gameboy, Densom TI-Nanolog, Matshisita Electric Works, and Fujikura. At one point, there were several Japanese MEMS competitors, but they have fallen out because of they were not profitable, according to Omron.

The piezoresistive pressure sensors were first produced in 1981. In 1990, the Tsukuba MEMS laboratory was initiated. In 1994, a capacitive pressure sensor was developed, and in 1995, a capacitive accelerometer was developed (glass-silicon-glass). As of 2000, 8 million units have been shipped for all MEMS devices. All production is bulk micromachining on 4-inch wafers. The applications are blood pressure monitors, leak detection, and suspension control for automotive. Pictures of Omron products can be found below.

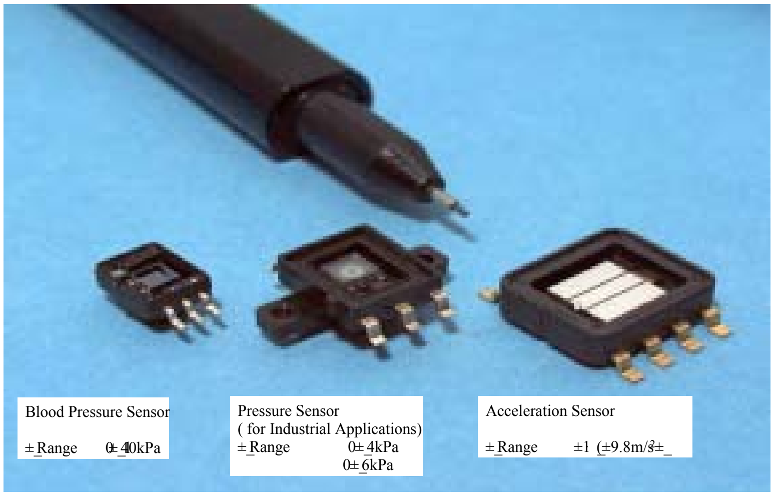

Figure B.15. Silicon capacitive micromachined sensors (total shipment over 8 million chips).

In 1998, Omron's MEMS division became a profit center (not just a cost center). Omron is interested in "harvesting" bulk micromachining technology to develop a profitable business. To do this, Omron is looking for a good partner and for acquisitions. Currently, Omron is focused on becoming a profitable MEMS business in the short-term and on developing new MEMS and CMOS-MEMS technology for the long-term. They are expecting their first profitable month within the next few months, in large part because of yields in excess of 80%.

The vision is to be a major MEMS supplier and fabricator in the world through expanding the bulk MEMS business and to develop/acquire surface MEMS technology to realize CMOS integrated surface MEMS (e.g., ADXL). In the shorter-term, they must capitalize on profits from the existing bulk micromachining technology.

The MEMS products in Omron are blood pressure sensors (0–40 kPa), pressure sensors for industrial applications (0–4-6 kPa), and acceleration sensors (+/-1g). All devices are capacitive with C_o of approximately 10 pF. The sensing electronics is not included on chip.

The blood pressure sensor is for a finger-type and wrist-type pressure sensor. A cap wafer with a diaphragm and a well is created. This is a backside exposure device to increase span and to isolate the wirebonds from the media. The silicon diaphragm has nitride on the backside to protect it from water/media.

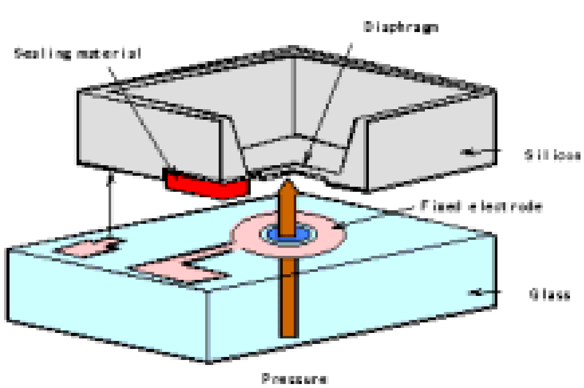

Figure B.16. OMRON pressure sensor for blood pressure meter with operating pressure range of 0–40 kPa.

The pressure sensor for gas detection is assembled into a circuit module that includes the analog custom IC chip. The top side is glass, and the lower side is silicon. A central pillar is included in a circular diaphragm.

This is used to improve linearity but it reduces span. It is patented. The capacitance C_o is 10 pF. At 6 kPa the capacitance changes to 15 pF.

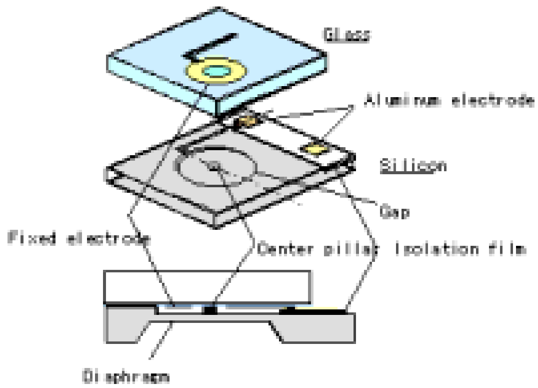

Figure B.17. OMRON low pressure sensor for industrial applications with an operating pressure range of 0–6 kPa.

The accelerometer is also bulk micromachined and capacitive. It is also assembled into a circuit module. The die size is 5 x 5 x 1.2 mm and also has three layers: glass, silicon, glass. The fixed electrodes are located on both glass layers with a bulk micromachined silicon wafer as the proof mass and moveable electrode.

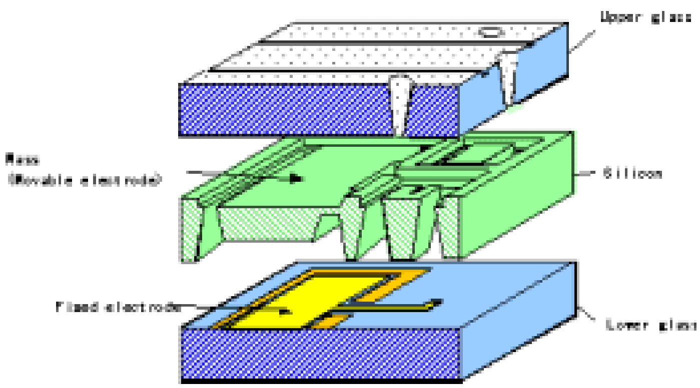

Figure B.18. OMRON acceleration sensor structure with a measurement range of 1G.

The reasons for going to surface micromachining are to get the new function, to reduce size, and to improve temperature performance through integration. The strategy with surface micromachining is to re-use the same equipment as a CMOS line. If only the sensor is produced, the foundry cannot be fully utilized, so integration of analog technology and re-use of the CMOS line is required.

The foundry will include silicon processes, MEMS processes (anodic bond, electrochemical etch, processing glass, etc.— see list of foundry processes available), and dicing of wafer. Customers assume the risk for the qualification. Other MEMS foundry services in Japan are Sumitomo Metal (6-inch surface micromachining), Dai Nippon Screen Printing (surface micromachining), and Olympus. There is also some MEMS foundry business in Taiwan. Their foundry service is available to all, including universities and/or businesses, but for a fee. Conflicts of interest are expected, but not considered a problem (because the semiconductor business is described as “shaking hands and punching each other” by Omron).

MMR TECHNOLOGY DEVELOPMENT OVERVIEW

The MMR business is a 4-inch wafer bulk micromachining process. There are about 700 die per wafer. The devices are 2 mm x 3 mm x 1 mm with chip and cap. Another company in Japan is not performing the packaging in plastic or ceramic. An 8 x 8 MMR array is also possible. The MMR also uses the glass-silicon-glass structure. The silicon is SOI, which has a 20 µm active layer with movable contact. The bottom side of the movable contact is made by a sputtered metal to make contact with the metal on the glass substrate (anodic bonding). Approximately 24V are required to make the contact.

The MMR is compared with SSR (solid-state relays) and EMR (electro-mechanical relays) in Table B.1. The observable electrical life is greater than 100 Mcycles. The key improvement when compared with SSR and EMR is very good high frequency characteristics (several GHz), short operate time and very low power consumption. The cost comparison is approximately the same as the SSR but, currently, MMR is more expensive than EMR. The cost needs to be approximately one-third to one-fifth of what it is today. The MMR yield is much lower than EMR, for example. A concerted effort to improve the yield to more than 90% is required to make a profit. The learning curve for MMR is very slow. Stiction is the largest yield problem. The insertion loss is -0.5 dB/2 GHz, isolation is -45 dB/2 GHz, and the VSWR is 1.1/2 GHz.

This is for ATE applications. There are no sales yet; the MMR is still in development. The potential markets are for wireless LAN, RF measurements, digital consumer electronics, portable phones, and IC testers.

The MEMS Technology Related Organization is centralized in the Tsukuba and Kyoto sites. Their roadmap includes surface micromachined technology by 2005.

One other note: Omron has invested heavily in Ball Semiconductor and will continue this investment.

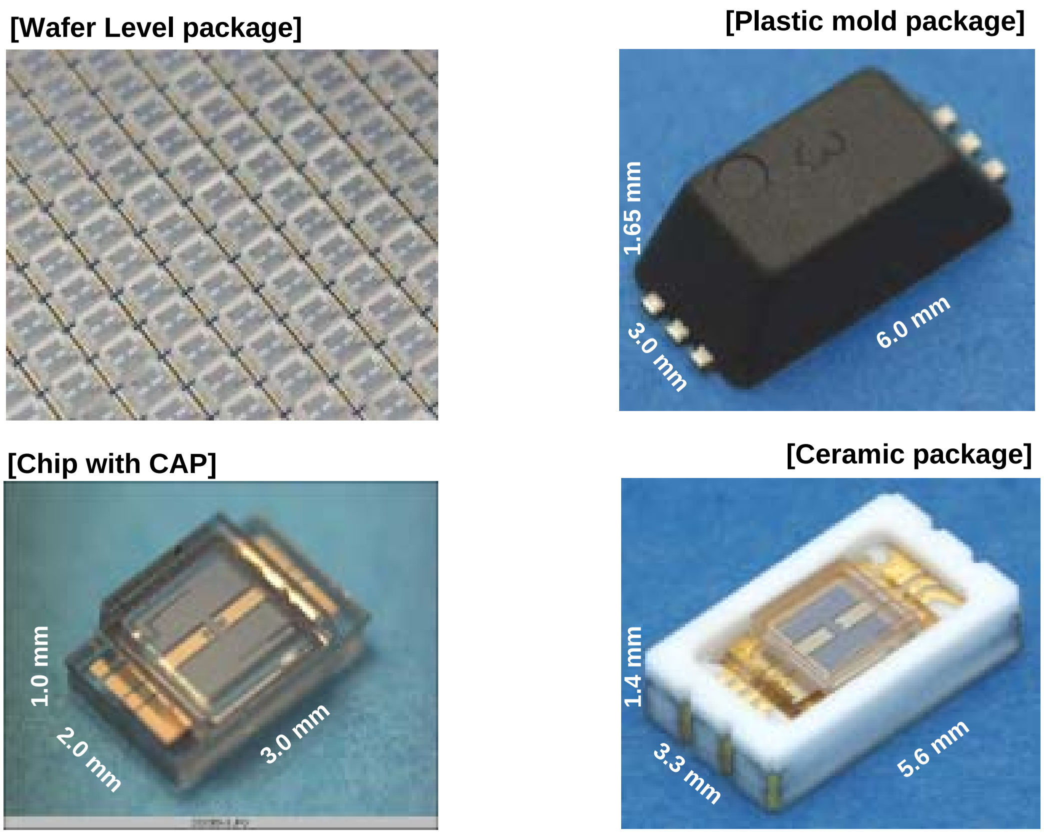

Figure B.19. Micromachined relays from OMRON.

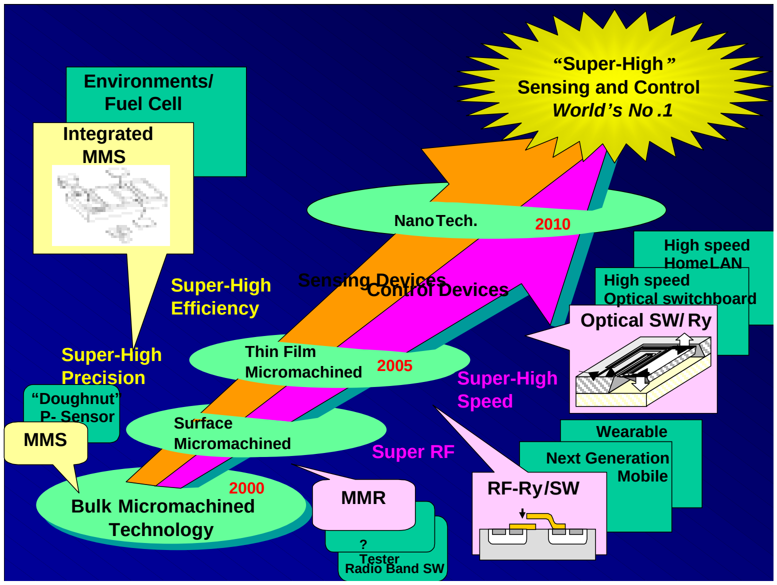

Figure B.20. The MEMS Technology Related Organization roadmap.

Table B.1
Comparison of Micromachined Relay (MMR), Solid State Relay (SSR), and Electro Mechanical Relay (EMR) Characteristics

	MMR	SSR	EMR
Size	Small (2 x 3 mm)	Small	Large
Relay resistance	Medium (400-500 mΩ)	High	Low
Switching power	Small (0.1 W)	Varies	Large
Breakdown voltage (between contacts)	Small (150 V)	Varies	Large
Operate/release time	Short (0.3 mSec)	Very short	Long
Electrical life	Medium (over 100 million cycles)	Very long	Medium
High frequency characteristics	Very good (Several GHz)	Not good	Good
Power consumption	Very low (0.05 mW)	Low	High
Drive voltage	Large (24 V)	Small	Small
Integration capability	Yes	Yes	No

SUMMARY AND FUTURE FOCUS OF THE MEMS AT OMRON

Omron believes that the MITI Micromachines Project was less efficient for short-term business goals because the selection of applications was not directly matched to commercial business, generating few commercial enterprises. Because Japan has focused on specific semiconductor fields (e.g., DRAM) and because other countries (like Korea) are starting to take some of that market share, the Japanese government is interested in reinvesting in other high technology areas. Omron believes that the Japanese government will continue to invest heavily in MEMS as one of these chosen fields.

Twenty years ago, Japan was more focused on copying the other advanced countries (United States and Europe). Today, Japan has the ability to scope out a new area, and thus, they are doing longer-term planning (10-year plans). Omron is doing this with MEMS. They are aggressively seeking to become a high volume supplier for MEMS products. Moreover, their approach is very flexible. They would consider developing the technology internally, partnering with a university to learn more about the technology, partnering with another company, and/or buying another company (even a U.S. company).

Omron's bottom line in MEMS products is not so good. The business must make money, and those at Omron believe that it will because they will be able to harvest products/foundry business from the basic technology that has been developed. It appears that late 2002/2003 will be the break-even point. Omron will use bulk micromachining products to make money and plan to move into surface micromachining.

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BACKGROUND AND GROUP OVERVIEW

Dr. Okuyama is a professor in the area of materials and devices in the Department of Physical Science at Osaka University. The group consists of Prof. Masanori Okuyama, Associate Prof. Minoru Noda, research associates Kaoru Yamashita and Takeshi Kanashima, three doctoral students, 11 Masters' students, five undergraduates, and approximately seven visiting researchers. The group has worked in a number of research areas, including: device physics and processing of non-standard IC materials (including ferroelectrics), uncooled infrared detectors based on bolometry, differential spectral imaging systems, and ultrasonic microarray sensors. Much of the work is oriented toward ferroelectric materials, used either as sensors or as actuators.

At the WTEC panel's visit, the Okuyama Group was concluding its participation in a multiyear project entitled 'SEIS' or the 'Super-Eye Image Sensor.' This project was funded by the Osaka Prefecture and was performed by Osaka University and a consortium of 13 companies. The five-year project began in 1996 and was funded at a level of approximately \$4.25 million, split approximately 40%/60% between the prefecture and the companies involved, respectively. Participating were approximately 32 part-time engineers from companies, three university researchers, and five students. The overall research vehicle was the fabrication of a sensing system that could mimic some of the functionality of the human senses, e.g., for robotics applications. Examples of devices fabricated in this project included infrared sensing; wavelength-differential imaging; ultrasonic sensing and imaging; flavor/smell sensing; MEMS sensors for acceleration, magnetic fields, and humidity; and development of the underlying silicon process technology. Although this project is now over, a microdevice center has been formed and will continue to fund subprojects. Some of these projects performed by the Okuyama Group were reported on individually and are given in more detail below.

MEMS R&D ACTIVITIES

Infrared Image Sensor

The infrared image sensor utilizes barium strontium titanate (BST) as a bolometric material. The approach was to determine the change in the dielectric constant of BST due to temperature fluctuations caused by exposure to infrared radiation. A silicon substrate is etched to form thermally isolated structures. The technology approach is wet etching of (110) silicon. Pt/Ti is used as a CMOS metallization, followed by BST deposition and an infrared-absorbing material on top. The Pt/Ti metallization is required since the film deposition temperatures are typically high (on the order of 400–600ºC). The device has a sensitivity of 1.2 kV/W and a detectivity (D*) of nearly $3x10^8$ cm $(Hz)^{0.5}$/W.

Wavelength Differential Imaging

The wavelength differential imaging project involved the use of stacked adjustable filters to enhance the ability to perceive small spectral changes among an unchanging background. The approach involves the fabrication of a variable interferometer using PZT actuation. The functional approach is to operate the device at two different interferometric spacings and sequentially read the spectrum of some object. Edge detection (e.g., to isolate a particular wavelength peak) in the transmittance vs. wavelength domain can then be performed by subtracting the two spectra. The approach was applied in the visible to image the spreading of deoxygenated hemoglobin in the human hand. It was also applied in the infrared to be able to selectively observe things like bodies of different temperatures as well as gas flow with specific infrared absorption spectra. It was also applied to the visualization of gas leakage and diffusion. Purported potential applications include the following: gas leakage, health diagnostics, ripeness of fruits, detection of rotting in foodstuffs, monitoring forest damage of plants, accurate color identification of clothes, and product inspection in a factory.

Ultrasonic Micro-Array Sensor

The ultrasonic micro-array sensor was a project of the New Energy and Technology Development Organization (NEDO) of Japan. The functional sensor element consists of a two micron thick silicon diaphragm with approximately 1 micron of PZT deposited on it using sol-gel approaches. Excitation or sensing of the PZT resulted in emission or detection of ultrasonic energy. The devices were typically operated in the sensing mode. The quality factor of the resonance of the membrane was approximately 250 at a resonant frequency of 176 kHz. This results in a sensitivity of approximately –40 dB (where 0 dB = 1 V/Pa), approximately 1 order of magnitude higher than bulk material. Multi-element arrays of 37 elements each were fabricated, which allowed localization of an impinging sound source. By changing the interconnect pattern, it is possible to change the directivity of the array. Currently, a bucket-brigade-based signal processing unit is being developed, and the ultimate goal is to integrate this unit on the same chip as the sensor array.

PARADIGM SHIFTS AND OUTLOOK

Much of the advanced work presented to the WTEC panel seemed to be focused on improving and exploiting the properties of ferroelectric materials, rather than on using advanced MEMS technologies in a sophisticated manner. This is consistent with the overall research report of the Okuyama Group, which emphasizes ferroelectric and materials development. It seems this group will continue its efforts in the ferroelectric area and the application of ferroelectric technology to MEMS. Funding for basic science was described as low in general, and the importance of application in securing funding was emphasized. Collaboration with companies, particularly small companies, has often been useful in applying for research funding. Consistent with the shift toward the increasing importance of patents at Japanese universities over the past few years, a technology licensing office was started in April 2001. This office seems more regional in nature (Kansai, Osaka) rather than being focused directly on Osaka University. Prof. Noda stated that the group has now begun to aggressively patent its work.

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BACKGROUND

Prof. Takeda and his group are a highly productive experimental solid-state physics research team. The focus of the work is to understand the basic science of silicon nanostructures, rather than engineering applications. Over the past few years, Prof. Takeda has investigated the formation of nanoholes by the clustering of defects and discovered "nanochains," which consist of periodic silicon nanospheres covered and connected by a thin, amorphous silicon dioxide "chain." This discovery, and his group's subsequent progress toward understanding the physics of nanochain formation, is a major advance toward more self-organizing nanostructures.

RESEARCH ENVIRONMENT

Professor Takeda's research group is self-contained, having its own fabrication and analytical equipment. Shared laboratories for micro or nano fabrication are not available at Osaka University. His focus on silicon nanostructures, in contrast to carbon nanotubes, is based on the huge knowledge base for silicon processing technologies. As a result, the work in his group should be more easily exploited by the microelectronics industry.

The high degree of interest in nanotechnology in Japan has not translated into increased funding, with the exception of nanotubes. Professor Takeda feels that nanotubes are too narrow a focus and that funding should be spread across a variety of topics in nanotechnology. As discussed later in this report, his laboratory has excellent transmission-electron microscope facilities and has been highly productive, despite having a very limited set of fabrication equipment.

RESEARCH PROJECTS

Professor Takeda discussed two main research areas: silicon nanoholes and silicon nanochains. The former topic has grown out of his interest in silicon crystal defects. His lab has developed a novel technique for forming nanoholes in ultra-thin (100 nm or less) silicon membranes. A focused electron beam irradiation on one side of the membrane causes sputtering of silicon atoms on the opposite side. The resulting surface vacancies diffuse and coalesce to form shallow surface pits; their extension into the membrane is due to the uniaxial diffusion of surface vacancies on the walls. Their average diameter and density increase with increasing sample temperature. The dielectric constant of the resulting porous silicon is lower than that of crystalline silicon, implying that a periodic structure could be useful for a photonic bandgap structure.

The second topic, silicon-silicon dioxide nanochains, has attracted widespread interest in the scientific community. In 1998 Kohno and Takeda accidentally discovered that these unusual structures form spontaneously using a modified vapor-liquid-solid growth procedure. Recently, they have developed considerable insight into the growth mechanism for nanochains and applied this knowledge to obtain high yields of nanochains. The process [4] consists of heating, in a closed ampoule at a pressure of around 10 μTorr, a sample of {100} oriented silicon that is coated with 10 nm of gold and a small piece of (typically) lead. The sample was then moved to a new ampoule, evacuated to about the same pressure, and heated to 1230°C for two hours. The proposed mechanism for nanochain formation is the periodic instability in the contact angle of the gold-silicon droplet resulting in a variation in the diameter of the growing nanowire. Oxidation of the nanowire's surface, owing to oxygen outgassing from the glass ampoule, converts the thin sections into silicon oxide and the formation of the string of silicon nanocrystallites. For a typical growth condition, the diameter of the crystallites was about 10 nm and the spacing was about 35 nm [4]. The role of the tiny amount of added lead is to modify the interface tensions during nanowire growth. High yield growth of a dense carpet of nanochains can be achieved through this process.

The investigation of the optical and electronic properties of nanochains is being pursued in Prof. Takeda's group. The discovery and understanding of the self-organizing formation of periodic structures is clearly an important advance in nanotechnology, with potentially broad applications.

LABORATORY FACILITIES

Professor Takeda's fabrication equipment was quite rudimentary, consisting of a furnace, vacuum pumps, and silica tubes for containing the samples. The transmission electron microscopes (TEMs) were first-rate, however. Dr. Kohno had mounted a nanowire sample in one TEM for our inspection. Another TEM had been modified by adding *in situ* photoluminescence spectroscopy, which is valuable for studying defects in semiconductors.

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BACKGROUND

In 1995 Ritsumeikan completed its second campus at Biwako-Kusatsu. That same year, Prof. Sugiyama moved to Ritsumeikan from the Toyota Central Research Laboratory and was joined by professors Tabata and Konishi in 1996 to form the MEMS group. At the end of 2000, they established a new center in the university, the Research Institute for Microsystems Technology (RIMST), supported by the Ministry of Science and Technology as an "open research center for private universities." The center includes 50 member companies.

RESEARCH ENVIRONMENT

Ritsumeikan aspires to be the MEMS flagship for the Kansai area, with facilities second only to those of Tohoku and Tokyo. There is a particular push towards technology transfer to industry through the RIMST member companies and the coordination of MEMS foundry services.

Fifty member companies, mostly from the Kansai area, pay $1000 per year in exchange for seminars and research reports. Two or three visiting engineers from industry work in each professor's lab. In the new RIMST building under construction, office space is specifically allocated for such visitors. A new technology licensing office (TLO) has been started in 2001. The government is providing for half of the cost of the office for the first five years. If a professor pays the costs of obtaining a patent, he retains all of the rights; otherwise the royalties are split with a third each going to the researcher, the university, and the TLO. In the case of industrial visitors, patent royalties are usually split 50-50 between the university and company.

The RIMST professors provide a strong teaching curriculum, offering four graduate-level courses: MEMS systems, devices, processes, and materials. Student interest is strong, with 80 students enrolled in the classes. However, each course is offered once every two years, and students usually don't take all four since they try to finish their coursework in one year. Ritsumeikan also includes a junior high and high school. MEMS seminars and MEMS open house sessions for high school students are part of an effort to encourage interest in science among younger students.

Professor Sugiyama has founded a company to organize a foundry system called the Multi-user Integration Chip Service (MICS). Three processes will be offered: analog IC, done at Olympus; surface micromachining, done at Yokogawa; and LIGA, provided by Ritsumeikan.

RESEARCH PROJECTS

LIGA is a particular strength at Ritsumeikan, capitalizing on the synchrotron facility located on campus. A variety of structures beyond the typical extruded 2-D LIGA shapes are being realized. One method employs depth control through varying the exposure. Another method uses direct ablation of material at arbitrary angles of tilt and rotation.

A number of applications of the LIGA process were shown. The depth-controlled LIGA process was used to fabricate a micro lens array. Lab-on-a-chip DNA analysis has been demonstrated in a PMMA micro capillary array chip. In addition, mechanical socket and plug connectors were shown. Also, a device with tunable acoustic absorption characteristics was created using an array of Helmholtz resonators with mechanically adjustable cavity lengths. Finally, LIGA-fabricated thick-film magnetic cores are intended for use in making lighter power supplies.

A 53-nm silicon nanowire was shown. Professor Isono is studying new physical effects in the nano regime, such as those found in quantum effect transistors. The word "nano" instead of "micro" was considered for use in the RIMST title, but "micro" was chosen to convey a sense of nearer term applications for industry.

Some sensors were shown, such as a low-g capacitive sensing accelerometer and a high-pressure piezoresistive pressure sensor. Also a gyroscope that utilizes the circular movement of a point-mass mounted on pillar was shown. This is currently hand-assembled, but a LIGA process is under development.

Finally, a piezoelectric bimorph micro valve was shown, as well as a self-supporting polysilicon thermopile for electricity generation, fabricated in a standard CMOS MICS process.

LABORATORY FACILITIES

Ritsumeikan has well-equipped facilities for MEMS research and is expanding. A new building for RIMST, contiguous to the synchrotron radiation facility, is scheduled for completion next May. The center will include facilities for e-beam lithography, microfabrication processes, photolithography, synchrotron radiation, and microsystem design. All of the major CAD tools are available for use, including MEMCAD/IDEAS, Intellisuite, MEMS Pro, ANSYS, Mark (FEA), MicroCAD, and anisotropic etch simulation programs. The microsystems lab currently employs only two engineers.

The panel toured the synchrotron facility. There are three beam lines dedicated for LIGA, with one to be added. One line, used by Prof. Tabata, has the capability for multiaxis positioning of both the mask and substrate to achieve complex structures. Another line, for Prof. Sugiyama, is used for the ablation of Teflon. The third line is used for standard LIGA. No VLSI research is being performed in this facility. The focus of the facility is split between materials research (i.e. bandgap characterization, crystal diffraction, etc.) and MEMS.

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FROM SHINAGAWA STATION TO SONY HEADQUARTER

On the way to Sony's headquarters, located around the Takanawa and Gotenyama areas in Shinagawa-ku, Tokyo, the WTEC travelers suddenly noticed that we were surrounded by numerous Sony buildings, passing "Sony 2 Building," "Sony 3 Building," "Sony 10 Building," … on "Sony Street." The headquarters building also has a museum, displaying an impressive array of historical Sony products up to the latest electronics products sold currently. One of the oldest displayed was an electric rice cooker before the age of transistor radios. I was caught by many flashbacks and then started remembering many of my memories associated with those Sony products on display. A part of the museum also had a section for environmentally conscious research, manufacturing, and products, indicating Sony's strong commitment to environmental protection and management of manufacturing. One of them that is based on "d-limonene" brought into the fabrication processes, was presented during the panel's visit.

PRESENTATION BY MR. MATSUMOTO

Mr. Matsumoto works in corporate technology, where he is responsible for technology evaluation, mainly in material and device technologies. He provided us with a glimpse of Sony's traditional creative energy associated with the corporate research philosophy. Mr. Matsumoto gave us a Sony Group overview (*Electronics, Entertainment, Games, Internet Communication Service, and Financial Service—connected by Global Hub*), showing schematic organizational charts, focusing on the electronics organizations, composed of Sony Electronics itself and other significant subsidiaries (Sony Computer Entertainment, Sony Communication Network, and Sony-Ericsson Mobile Communications). Sony Electronics itself includes the Electronics Headquarters, Sales, the manufacturing sector, Corporate Laboratories, and many product-segmented small companies; ERC (e.g., "Aibo," a famous robot dog), the Semiconductor Network Company (NC), CNC (core technology), Display NC, Home NC, Broadband NC, Mobile NC, Telecom Service, S&S (Silicon & Software) Architecture Center, and Network & Software Technology Center; Corporate Lab structures.

One of Sony's unique activities is coming from the Computer Science Lab (CSL) where the engineering and research activities are almost independent from business issues, according to Mr. Matsumoto. One of the panel members asked a question about a MEMS foundry in the U.S. branch of Sony (http://www.foundry.sony.com/default.shtml). The San Antonio foundry provides services of relatively "standard" MEMS processes, implying presumably that much of the state-of-the-art MEMS operations might not be happening there. The panel had the strong impression that the state-of-the-art operations might still be partly centralized in key locations in Japan.

Mr. Matsumoto explained that Sony's expectations and understanding are the R&D, "applicable to consumer electronics, low cost, and high performance" and "fabrications compatible with CMOS." Sony is currently evaluating the optical, RF, and microfluidics areas. External collaborations include Prof. Esashi (Tohoku

University) for microfluidics with *ePrint* company, and Sony is a MMC supporting member for core technology and networking sections. Sony also maintains ongoing information exchange channels with BSAC of UC Berkeley. Advanced collaboration with Tohoku University is active and ongoing. The importance of Sony's relationship with universities was emphasized as the key to "educating new people" (i.e., students), regarding Sony's culture.

When they asked if Sony has ever surveyed the various MEMS areas, the panel was told that the division represented by Mr. Shimada (Chief Technology Expert, MEMS Development Department, LSI Technology Development Division) had done some evaluation of MEMS in the past: examining ways to use the devices, ways to make them in house, what is available to buy, etc. Stimulated by nanotechnology initiatives in the United States, the Japanese government now wants to accelerate the funding for national and public labs and then to collaborate with these labs to get the outcome benefits. U.S.-Japanese collaborations have the problem of distance (especially for communication) and time differences since the Japanese think that videoconferencing does not work and that team communications need to be face-to-face. Regarding the quality of MEMS facilities in Japan, the panel heard that many U.S. universities have better fabrication facilities than Japanese universities. For people exchange programs, Sony covers all the expenses when sending employees to universities for degree or non-degree programs.

PRESENTATIONS BY DR. YUTAKA TAKEI

Dr. Takei (*General Manager, 4GP, CT Development Center*), who mainly works in R&D, presented several overhead foils, covering selected latest areas of the division's MEMS research activities. His division, the Core Technology and Network Company (CNC) has the Nishi Battery Lab and Kubota Opto-Electronics Lab and works with the New Display Device Division.

The first presentation described "GP4 (Thin-Film and Plastic Technology for MEMS)—for productions, including PBII/plastic surface modification; thin-film coating (FCVA); and thin-film coating on plastic AR film, dichroic mirror "film" (optical coating). Plastics' weakness is the mechanical property of the surface that needs some modifications, and thin film was fabricated onto plastics as a part of surface MEMS for multi-color optical film coating. Actual samples were shown and passed around during the presentation. Another presentation was based on the paper on plasma-based ion-implantation (PBII) by Minehiro Tonosaki (2000) with some practical applications to high impact resistance plastic hard disk. Compared to semi-conductors, ion implantation on plastics requires low temperatures (< 100°C) and has no need for annealing in order to heal.

Thin films on plastics crack due to tensile stress. The stress of Ta-C (tetrahedral amorphous carbon) thin film is, however, compressive on a Si or metal surface. PBII was created by UC Berkeley/LBNL with the ion source from gas material (e.g., carbon) with a bi-polar pulse (-20kV/+10kV, 30 μs pulse; 10^{16} ions/cm^2; 1 min process time; 5×10^{-4} Pa operating pressure) and a filtered cathodic vacuum ion chamber. A bi-polar pulse attracts ions instead of hitting them as in conventional methods. The application includes a high impact resistance plastic disk where the impact resistance is 3x and higher than that of a Ni-P plated conventional aluminum disk; however, currently the cost is high. Another application is the "Micro-structure fabricated plastics using PBII and d-limonene (APO with a five-member ring) process."

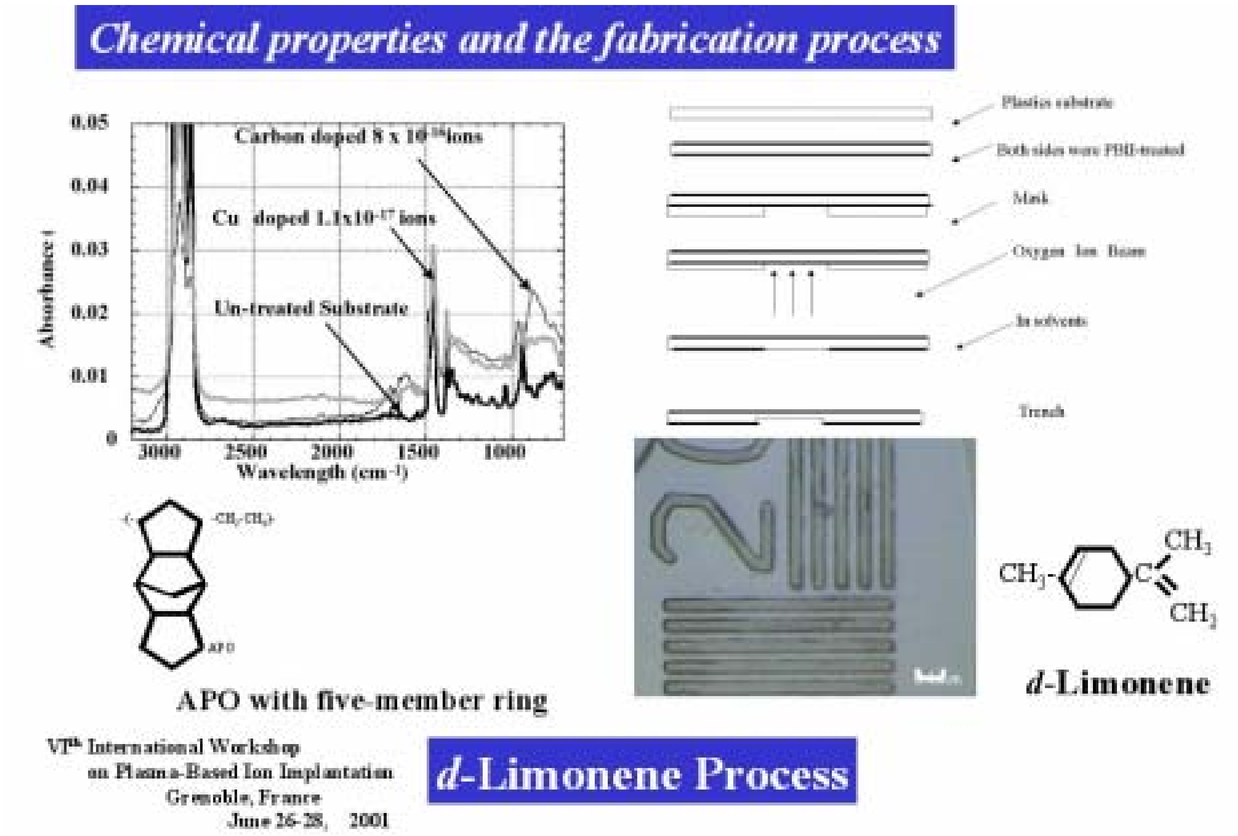

Figure B.21. Micro-structure fabricated plastics–chemical properties and the fabrication process.

Filtered cathodic (i.e., carbon) vacuum arc (FCVA) is a new type of deposition where adhesiveness is high (because the deposition energy is more than 100 times higher than in the evaporation method and is greater than 10 times higher than sputtering) and the surface for MEMS is impurity free. “Multi-Layer Dichroic Coating on Plastic Webs” for rear projection TV could be made from multi-layers (25 layers) with SiO_2, Nb_2O_5, SiO_2, ... adhesive layer/SiOx, hard coat (acrylic), ..., PET. The PET plastic film (sputter-coated on PET laminated to glass. Sony WEGA (flat screen) with anti-reflection, anti-EM emission, and anti-static characteristics is the product based on this technology. It was very interesting to note that often Sony brings a design to the vendor, who builds a manufacturing machine, and the vendor will sell the product to others after 3–4 cycles of productions have been licensed from Sony.

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BACKGROUND

Under the leadership of Prof. Masayoshi Esashi, Tohoku University has been active in MEMS research for well over two decades. The MEMS research group consists of Assistant Professor Takahito Ono and Lecturer Shuji Tanaka, research associates, postdoctoral researchers, visiting industrial researchers, and graduate students. This very productive group is well known for the development of new microfabrication technologies for a variety of applications. Professor Esashi is affiliated with both the Venture Business Laboratory (VBL) and the New Industry Creation Hatchery Center (NICHe). His group's current research themes include active catheter-based maintenance systems for extending the life of machinery, wafer-level MEMS encapsulation, micro energy sources, component development for information technology (optical switches, data storage), and nanomachined devices.

In 1996, Tohoku University established the VBL, for which a new building called the micromachining facility was constructed. There is a nanomachining facility besides the micromachining facility. In 1999, NICHe was established at Tohoku University, and Prof. Esashi was appointed the leader of microsystems research, with a research theme of applications directed at energy and resource conservation. NICHe is a new phenomenon in Japanese academic institutions, in that it has a liaison office to promote ties with industry, a technology licensing arm, and an incubator for promoting the formation of start-up companies. Lead faculty at NICHe are freed from the management overhead of their home departments and furthermore are not obligated to teach.

RESEARCH ENVIRONMENT

Professor Esashi's laboratory hosts many visitors from companies. The laboratory maintains an "open" policy so that researchers can share information across research projects. He mentioned that companies should patent their ideas prior to coming to Tohoku and that inventions developed there would be considered jointly held between the company and the university. This policy is working well and allows visitors from competing companies to work on projects at NICHe.

The laboratory facilities are designed according to Prof. Esashi's "slim" philosophy, which he learned at Tohoku under his thesis advisor, Prof. Nishizawa at the Semiconductor Research Institute. This philosophy is to develop fabrication equipment specifically for academic research that uses smaller wafers (and thus, fewer materials) and that is robust and flexible. Much of the fabrication equipment has been designed, built, and currently maintained by graduate students and postdoctoral researchers. The cost to access the laboratory is very low, about $30,000 per year, which is possible because of the many (an average of 15) companies that dispatch their researchers to his laboratory and of government subsidies of about $400,000 per year for the operating costs of the VBL.

The Esashi group has a long history of successful technology transfer dating to the 1970s with the portable pH sensor based on an ion-sensitive FET. A capacitive pressure sensor developed at Tohoku is the basis of several products of the Toyoda Machine Works. Another commercial development is an immobilized enzyme biosensor for detecting pyroli bacteria, the cause of many stomach ulcers. Nihon Kohden has products based on this device. Recently, shape-memory actuators (coil and spring) have been used to make a steerable catheter with 0.5 mm outer diameter. Dr. Yoichi Haga, a medical doctor working as a research associate in his laboratory, is launching a spin-off company to commercialize the active catheter.

RESEARCH PROJECTS

At NICHE, Prof. Esashi is the leader of the Energy and Natural Resource Conservation research activity, which describes a primary motivation for his research activities. He provided an overview of several recent projects. Many of them exploit wafer bonding, a core fabrication technology at Tohoku. By bonding pyrex wafers with electrical feedthroughs to silicon device wafers, Prof. Esashi's group is working toward an inexpensive wafer-scale hermetic packaging technology for MEMS. High density electrical feedthrough can be fabricated by deep RIE of the pyrex glass and metal electroplating inside holes. He noted that this approach could enable small-scale production of MEMS, by eliminating expensive traditional packaging processes.

Among the projects outlined was a spinning, electrostatically levitated mass gyroscope developed cooperating with Tokimec, a Japanese manufacturer of navigation-grade gyroscopes. This device is capable of simultaneous measurement of all three axes of linear acceleration and two axes of rotation. Tokimec is preparing to commercialize the device. A safing switch for side-impact airbag sensors was described, in which a spring contact was used as an anti-stiction solution. A silicon micromachined probe card for VSLI testing, which utilized TiC as a wear-resistant material for the contacting probe tips, was described. Spray photoresist and an Ushio projection lithography system with a 100 µm depth-of-focus were needed for 3-D patterning on the tips. Tokyo Electron, a manufacturer of IC test equipment, sponsors this project.

Ball Semiconductor, a start-up in Dallas, Texas, has close ties with the Esashi laboratory, with four members from his laboratory joining this company. A recent project that also involves Tokimec uses a 1 mm diameter silicon ball for inertial sensing. A polysilicon sacrificial layer is removed in a novel way: XeF_2 permeates a porous ceramic coating to free the ball. Electrodes patterned around the ball are used to levitate it, with the electrostatic forces required to maintain a stable position reflecting the inertial forces on the ball. This project has been reported at the MEMS-02 Conference in Las Vegas.

Professor Shuji Tanaka outlined research in the area of micro power generation and microfluidic control. He is leading a two-pronged approach to developing a small gas turbine by investigating both conventional mechanical machining and lithography-based fabrication technologies. A prototype rotor is 5 mm in diameter and fabricated from SiN ceramics by nitridation of silicon powder. Sintering, using sacrificial silicon molds, leads to parts with small deformation and shrinkage. The assembly of this mechanically complicated device is a major hurdle. Regardless of the technology used in the demonstration, Prof. Tanaka points out that it is very important to build and test a small turbine. Cost is felt to be a major issue for many consumer applications but not, for example, in the case of power sources for a humanoid robot.

Multi-nanoprobe data storage is the subject of a recent Ph.D. thesis by Dong Wong Li, who has recently joined IBM Research's Zurich laboratory. The leader of this project is Associate Prof. Takahito Ono. There are 32×32 arrayed probes, each probe with an integrated heater tip being used to write the 30 nm x 30 nm area bits onto a DVD-RAM media. This has been presented at MEMS-01 and at MEMS-02. Since this data storage device uses contact recording, wear is a major issue. A visiting researcher from the Industrial Technology Research Institute in Taiwan is involved in this project.

Nanostructures have been studied by Associate Prof. Takahito Ono in this laboratory using several techniques. Carbon nanotubes have been selectively grown on AFM tips. Resonance of the AFM provides information on the mass of the nanotubes, which is greatly increased by hydrogen absorption. Given the outstanding facilities in the nanomachining facility, Prof. Esashi and his group are well-positioned for ground-breaking research in the practical application of nanostructures for sensor applications. Professor Esashi is involved with the Japanese government in planning a new nanotechnology initiative, which was scheduled to start in 2002.

Education: Professor Esashi, as a leader in NICHe, is freed from his regular teaching obligations. He does, however, teach one course a week and a 3-day short course in the summer as a continuing education course for engineers from industry. Last summer, it was oversubscribed by a factor of two. However, regular Tohoku University students do not appear to be overly interested in MEMS compared to other areas of engineering.

LABORATORY FACILITIES

The research facilities at Tohoku are outstanding and include a micromachining facility; a nanomachining facility; and several optical, surface-science, and general test labs. The analytical, synthesis, and evaluation tools in the nanomachining facility were particularly impressive. In addition, there is a well-equipped traditional machine shop and a new milling machine capable of 70 nm precision, which is used for the micro turbine project. Most of the newer equipment in the facilities has been purchased from vendors, which is possible due to the large (about $1 million per year) annual budget of which half is from the government and the other half is from industry. Much of the older equipment is customized or built from scratch.

VBL Micromachining Lab

This 600 m^2 laboratory is based on 2-inch wafer facility and contains a variety of process tools, most of which are commercial systems. The process equipment includes the following:

- Lithography: high-speed direct-write e-beam, 5X reduction optical stepper, mask making
- Deposition: sputtering, CVD (including tungsten), and laser evaporation
- Etching: two 4-inch-capable STS deep RIE tools, fast ion beam, eximer laser ablation for polymers, laser-assisted silicon wet etching apparatus, focused-ion beam, XeF_2, femto-second laser
- Wafer bonding: multi-stack wafer aligner
- Ion implantation: very simple, robust machine
- Analytical tools: SIMS, SEM, thin-film mechanical property tester,

Nanomachining Laboratory

- CVD synthesis: carbon nanotube growth with integral FTIR, diamond
- E-beam lithography
- Optical, E-beam mask making
- Photon counting video camera for electrical breakdown study
- Analytical tools: vacuum STM, near-field optical imaging, optical resonant frequency pickup

2 cm Laboratory

This laboratory is for processing 2 cm x 2 cm square wafers and contains home-made process equipment.

- Etching: inductively coupled deep-RIE for glass, oxygen RIE for polyimide, PZT deposition, APCVD for polysilicon, oxide, wet silicon etching
- Deposition: 30 µm-thick TEOS oxide CVD, parylene, diffusion tubes
- Lithography: Karl Suss contact aligner
- Rapid-thermal annealing
- Electroplating

Machine Tools

- 5-axis milling machining (Zephyros) with 70 nm jitter in rotation
- stainless steel lamination

Test Labs

There are spacious facilities in VBL for testing microsensors and microactuators using electrical and optical techniques. One room contained a museum of silicon MEMS.

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TOYOTA CENTRAL R&D LABORATORY OVERVIEW

The Toyota Central R&D facility (CRDL) was established to pursue fundamental technologies for the Toyota group. There are several “stockholder” companies in Toyota’s CRDL, Inc. The goal of the CRDL is to develop research ideas to transfer to component production facilities within the Toyota Motor Company keiretsu (e.g., to Denso for semiconductor components). Key topical areas of research include the following:

1. Environment: The labs, for example, are doing combustion analysis to continue developing the perfect “green” car. This includes in-cylinder observation to enhance performance while minimizing emissions. Also, catalytic converter research is being performed to minimize the nitrous oxide emissions in exhaust gases. Technology being developed includes titanium metal matrix composites for improving the lifetime of moving automotive engine parts. Also, inorganic electroluminescent thin films for display technology is being developed to reduce operating voltage and provide better high temperature performance. Rubber recycling research that facilitates higher yield in reclaiming rubber has led to a technique to break cross-linking points. And, fuel cell research using hydrogen and oxygen electrochemical reactions (membrane electrode arrays) is ongoing.
2. Safety: a finite element model of the human body, for example, has been developed for accident simulations. An outcome of this research has been seats that lessen whiplash injury.
3. Information and Communications: electronically scanned millimeter-wave automotive radar, for example, be used for object and lane detection systems. Ultimately, such radar would be applied to crash avoidance systems. Also, traffic simulations and controls are being researched and have been demonstrated at the Nagano Olympics.

The Toyota CRDL is active in research meetings (e.g., JSME). The corporate culture seems to empower individuality and make all staff members enthusiastic.

TOYOTA CENTRAL R&D LABORATORY SENSOR OVERVIEW

The Toyota CRDL organization includes mechanical engineering, system engineering & electronics, materials, research fundamental technology, and frontier research. The sensor group is within the Electronics Device Division.

The Electronic Device Division includes power semiconductor devices (for electrical vehicles), reliability physics of ICs (especially gate oxidation), and sensor technology.

The goal of the Toyota CRDL sensor development is to develop sensor research concepts for the Toyota Motor Corporation (sensor systems application). These technologies, once through the research stage, are transferred to Toyota Motor Group semiconductor supply partners (e.g., Denso Corporation) to fabricate the sensors. The focus has been on surface micromachining. Technology has been developed for sensor fabrication (stiction, vacuum sealing), material characterization (tensile strength measurement), and sensing mechanical analysis. To date, the technology has been three-layer polysilicon surface micromachining. Examples of specific projects follow.

POLYSILICON VIBRATING GYROSCOPE VACUUM-ENCAPSULATED IN AN ON-CHIP MICRO CHAMBER (TSUCHIYA)

This gyroscope is expected to be used for vehicle dynamics. The goal is small and low cost. The gyroscope is required to be encapsulated in a vacuum because of the small mass and small Coriolis force. Vacuum sealing is required. To date, glass or silicon cap anodic bonding is used for sealing.

The basic gyroscope is a polysilicon multilayer structure fabrication without CMP (Tsuchiya, 2000). On-chip vacuum encapsulation is being attempted by using HF permeable films (Tsuchiya, 2001a). An opening is created in the structural material and backfilled with thin (0.1 µm) phosphorus-doped polysilicon. The sacrificial layer etching is performed through the thin polysilicon, so no direct etch openings are used. Following sacrificial layer etching, a sealing process is performed with silicon nitride.

The gyroscope technology is created with a three-layer polysilicon structure (Tsuchiya 2000; Tsuchiya 2001). The second layer is the resonator, and the third layer is the sealing chamber with pillars. The third layer is polysilicon and sealed in vacuum with plasma CVD silicon nitride. The p-doped, 0.1 um polysilicon film is permeated with HF. The deflection of the sealing film must be minimized, so a pillar is needed (otherwise, the silicon nitride must be thickened to over 10 µm).

A compensation oxide is used around the pillar to minimize the lack of lateral travel because of the pillar (etch profile). Mechanical shock is not so severe as in accelerometers. Pillar structure optimization was used with FEM analysis (through the use of NASTRAN) and analytical methods that provide the spacing (75 µm) is needed. This is optimized for air pressure only. The resonant properties are measured with the sensor (Q) as a function of pressure. Using the Q as a function of time, reliability evaluations could be gleaned. The initial chamber pressure is 250 Pa; after 2 years, it increases to only approximately 350 Pa. The output of the sensor is not as good as a 3-layer type. It needs to be 1 deg/sec, and the on-chip encapsulation is only 5 deg/sec.

Toyota CRDL is in discussion with Denso for producing this device. There are still several issues: cost, reliability, and performance, but the major issue is cost. Currently, the gyroscope project has ended, and another project has started and is consuming the 4-5 person project team.

TENSILE TESTING OF THIN FILMS USING ELECTROSTATIC GRIP

MEMS devices include many thin films (brittle), but the reliability is unclear. Strength properties are a large concern. A proposal for an electrostatic force grip system has been made films (Tsuchiya, 1996; LaVan 2001; Tsuchiya, 2001b). Thin film measurements include LPCVD polysilicon, PECVD silicon dioxide, and PECVD silicon nitride. The system is a cantilever beam with a large paddle on the free end and a dog-bone shape on the paddle. The principle for chucking the specimen is to use electrostatic force on the sample until the dog bone breaks.

The testers are in vacuum (SEM) or in air. Samples less than 5 µm thick can be tested. An electrostatic actuator is used with a load cell to measure tensile strength. Brittle fracture is observed in all films. The defects on the surface initiate the fracture. High strength was observed. Air does reduce the tensile strength, especially with SiO_2 (by 50%) at room temperature. The conclusion is that accelerometers and angular rate sensors must be packaged in inert gas.

Toyota CRDL is participating in the standardization activities in Japan as a part of NEDO's Micromachine Center activities in Japan. The program focus is on tensile testing, including a round robin tester: Nagoya/Sato, ME Labs (AIST, MITI), the Tokyo Institute of Technology/Higo, Gunma/Saotome, Toyota CRDL. Also, Toyota CRDL has performed the round robin test with Sandia, Caltech, and Johns Hopkins to compare results with rest of the world.

A NEW PROCESSING TECHNIQUE TO PREVENT STICTION USING SILICON SELECTIVE ETCHING FOR SOI-MEMS (FUJITSUKA)

SOI can be used to create thicker devices with easier CMOS integration, but it is expensive and exhibits stiction. Currently, Toyota CRDL is using an applied materials deep RIE for these structures. Several alternative techniques have been surveyed, including: vapor HF, sublimation drying, photoresist ashing, supercritical CO_2, SAM, and fluorocarbon polymers (special apparatus, materials, thermal stability). However, a single process was not available and reliable for both in-use and release stiction. The purpose of this work was to develop a single, reliable technique to minimize both in-use and release stiction (Fujitsuka in press).

Silicon etching of HF-HNO_3 (3 parts)-CH_3COOH (8 parts) was used following sacrificial layer etching to undercut the movable structure. The advantage is that the substrate is roughened, asperities (dimples—micropyramids) are formed, and an increase in the z-axis gap occurs. Release stiction, caused by capillary forces, is reduced because the contact angle of water increases dramatically on the substrate after silicon etching. This technique is only valid for vertical stiction (not for lateral stiction). Nevertheless, the maximum detachment length was over 2 mm (using a technique similar to Mastrangelo et al.) vs. 200 µm with the previous technique.

WTEC PRESENTATION

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix C). A summary of the U.S. MEMS survey was provided to the Toyota CRDL (Appendix C). Very brief reviews of the research at each of the U.S. panel members were presented (Appendix B).

SUMMARY AND FUTURE FOCUS FOR TOYOTA CENTRAL R&D LABS

For Toyota CRDL, converting the automotive system to electronic systems drives the need for additional sensors (e.g., MEMS). Toyota CRDL is chartered to produce technology for the Toyota group (e.g., Denso, first). Research will continue to support this conversion; however, making the conversion is difficult because the internal research infrastructure is not available. There are approximately 10 MEMS people in Toyota CRDL—not a critical mass of researchers. Co-research is being performed with Denso to augment the personnel. In the future, it may be possible for Toyota CRDL to use external foundries like Omron.

Another issue with these sensor devices in the automotive arena is power. How will the micro-power generation be created? Toyota CRDL is interested in several techniques: e.g., scavenging from the environment (Seiko watch, tire rotation), micro fuel cells, combustion systems, etc. This would open the alternative of using wireless automotive sensor nodes. However, little progress has been made to date on this front.

When asked "what is the status of MEMS research in Japan?", Toyota CRDL answers as follows: There is much technology for MEMS in the world, but few real applications require MEMS. Industrial research is very focused on making new products. There may be some devices—like optical MEMS—that may succeed in the commercial environment, but not many. Toyota is using accelerometers, pressure sensors, and gyroscopes from Denso, from Toyoda Machine Works, and from outside the Toyota keiretsu. Semiconductor MEMS devices require significant infrastructure, so to succeed, mass production is needed. With this large barrier to entry, success is very limited. External infrastructure, like foundries, could provide the needed infrastructure to create small volume fabrication that can then be transferred into high volume.

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WTEC PRESENTATION

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix C). A summary of the U.S. MEMS survey was provided to the Mr. Okada (Appendix C). Very brief reviews of the research at each of the U.S. panel members' institutions were presented (Appendix B).

WACOH COMPANY/DIVISION OVERVIEW

Wacoh was established in September 1988 with ¥1M and one employee. Prior to 1988, Mr. Okada worked in pressure sensor development for another company. He got his start in inertial sensing by reviewing the literature, especially Professor Ken Wise’s dissertation. During the first eight years, Mr. Okada worked alone, then acquired a staff as the company developed products. It currently employs seven people and has a budget of ¥30M.

Based on the work of Mr. Okada alone, the company has created a large patent portfolio: approximately 100 (U.S., Japanese, and European) patents. Mr. Okada has achieved a 98% acceptance rate on his disclosures vs. the average rate in Japan of approximately 50%. Currently, the patent portfolio cost ¥30M. The legal work for this intellectual property is outsourced.

Figure B.22. Mr. Kazuhiro Okada, President of Wacoh, showing the company’s patent awards.

The resulting business strategy and sources of revenue are as following:

- License micromachining technology
- Consult on sensor technology
- Obtain revenue from production and sales (including royalties) on:
  - 3-axis accelerometers: piezoresistive, capacitance, and piezoelectric (each technology has own characteristic and market)
  - 3-axis force sensors: capacitive (for example, for the IBM PC keyboard)
  - 2-axis angular rates: piezoelectric

The stated corporate policy, or long-range corporate plan is the following:

1. First stage, 1988–1993: create patent portfolio for 3-axis accelerometer, force sensor, angular rate sensor 6-axis motion sensor
2. Second stage, 1993-1998: product development on patents obtained
3. Third stage, 1998–2003: production and sales of developed products
4. Fourth stage: 2003-2005: introduction of publicly traded shares (then retire and farm)

Currently, Wacoh is looking for partners to outsource manufacture in the United States and in Europe. Wacoh would like to establish its business in the United States. In Japan, 5–10 companies are producing sensors for Wacoh, depending on the technology (some are silicon based and some are ceramic for the piezoelectric devices).

Not only is manufacturing outsourced, but much of the marketing and sales are outsourced as well, mainly to the manufacturing site organization. For example, the sensor technology for the Sony Aibo is sold directly from the manufacturing partner to Sony. Much of the marketing is done through word of mouth from academic meetings. After his first academic paper was presented in 1992 at a sensor's symposium in Japan, Mr. Okada received 1000 inquiries about his device for a year. He is also receiving significant inquiries through the Internet.

Venture business in Japan is challenging because there are funding limitations, the social environment does not encourage it, and there are significant personal ramifications for failure. In Japan, personal funding of new businesses is a necessity. There is very little venture capital, as there is in the United States. If one fails in Japan, the company loses everything, and it is impossible for the entrepreneur to start again. In fact, if a person goes bankrupt, he loses his right to vote. In the United States, it is much easier to obtain money and much less detrimental to take business risks, even if the result is bankruptcy. Wacoh is a corporation with stockholders, but initially, it required a loan with some collateral (Mr. Okada's property).

Starting Wacoh was a big risk. However, Mr. Okada did not want to work in a large company anymore, so he went against the advice of many of his friends and started the company anyway.

WACOH MEMS TECHNOLOGY OVERVIEW

The bulk micromachined or surface micromachined accelerometer typically is just 1-axis. Wacoh's technology is a 3-axis technology. These are boss-like proof mass structures that can be used for force sensing, accelerometers, angular rate sensors, and motion sensors, as shown in Figure B.23.

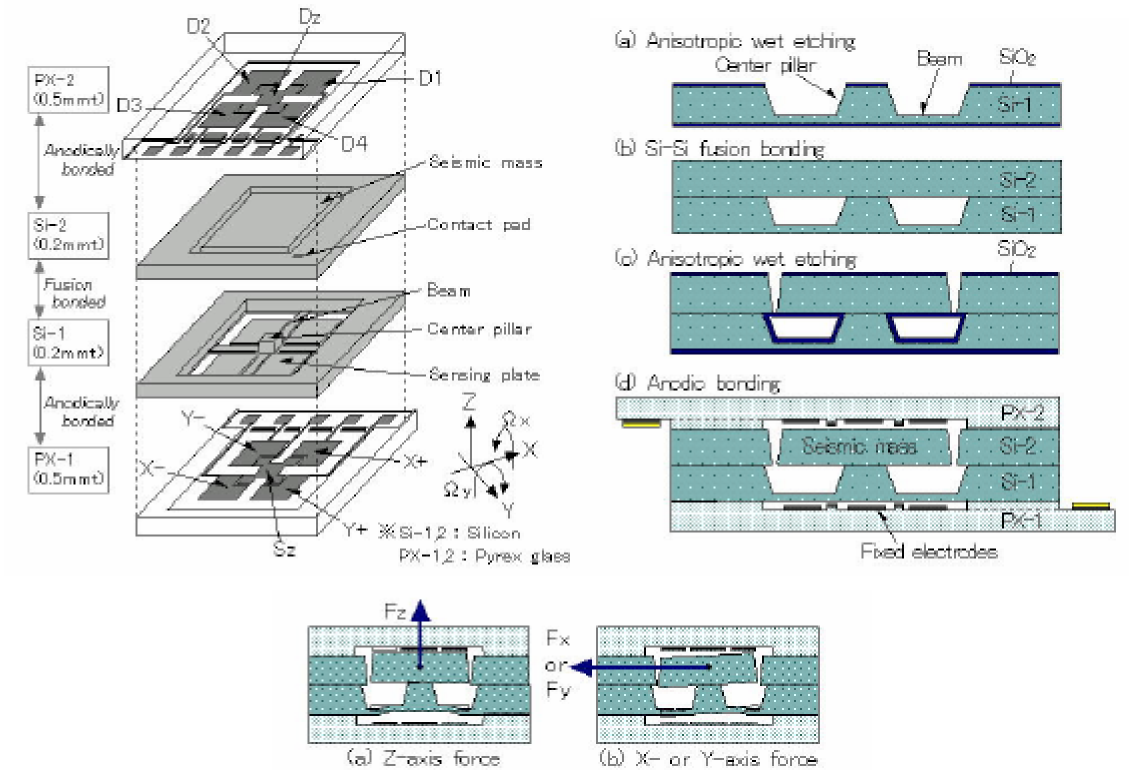

Figure B.23. The basic Wacoh micromachining technology (Watanabe 2001).

Three sensing mechanisms have been used for the accelerometer: piezoresistive (bridge), capacitive (second bonded wafer), and piezoelectric. In 1992, the first 3-axis accelerometer was developed and commercialized (5 mm x 5 mm). This product is fabricated by a Japanese company under NDA. The assembly was done in CerDIPs. All manufacturing has been outsourced. Complete product descriptions are available at http://www.wacoh.co.jp.

The capacitive accelerometer is 2.5 mm x 2.5 mm. The die size reduction has been enabled by deep RIE (STS) and SOI. The cost is 10% less than previous devices. This is a 2g device. Mr. Okada is very confident that Wacoh will win this market.

Also, Wacoh offers 3-axis accelerometers and 2-axis angular rate sensors using the same fundamental micromachining technology. The accelerometer sensitivity is 5.8 fF/g with less than 5% cross-axis sensitivity. The angular rate sensor is 2.8 aF/deg/s with less than 3% cross-axis sensitivity. Compared to the Systron Donner sensor, Wacoh's accelerometer has slightly more noise, but a similar performance. The Sony Aibo contains a Wacoh 3-axis acceleration sensor. The Sony Playstation Fishing game has a 3-axis acceleration sensor as well.

A 5-axis motion sensor has been developed, but it is not yet in production. A 6-axis motion sensor may be introduced in 2003.

A 3-axis force sensor is planned for future PDA or cell phone-human interfaces. In March 2003, a handset manufacturer is looking to add such a sensor.

Testing of each of these devices is mainly outsourced at the manufacturing company. However, Wacoh also has a lab near the Japan Sea.

DEMONSTRATIONS

Three demonstrations of the products in which Wacoh sensors are used were presented:

- Two-axis gyroscope—piezoelectric 2-axis gyroscope: dc to 20 Hz. -5 to 75ºC.
- Capacitive force sensor for PDA, cell phone, and possibly some notebook computers
- Gyroscope and accelerometers—Sony Aibo

SUMMARY: SMALL BUSINESS DEVELOPMENT IN JAPAN

Wacoh's initial funding was ¥1M. The company has always been in the black. Today, the capital stock is worth ¥30M.

The first development project was done jointly with a university. The investment is limited because of outsourcing. The manufacturing partners are also partially the sales and marketing arm of the organization. Therefore, the profit margin is quite high. Of the seven employees, five are engineers and Mr. Okada himself does some of the sales.

Foundry service is vital to the Wacoh business. Ten years ago, there were no foundries in Japan, and the level of the technology was quite low. Mr. Okada went to the foundries and trained the engineers himself to help develop the foundry service. The manufacturing company now has developed products beyond those for Wacoh. The manufacturing company is not an investor in Wacoh.

The ultimate goal in 2005 is to go public. Wacoh is also open to being bought out so that Mr. Okada can retire.

Wacoh has received no Japanese government funding. Wacoh did apply for funding through the Micromachine Project, but the application was not accepted. However, when asked whether government funding is a prerequisite for MEMS business success, Mr. Okada provided the following answer: the market will dictate the final assessment of a product. Even if the government provides funds, the market will define success. If there is a good project, the government should help with funding, but this is very difficult to evaluate.

Finally, the three-axis sensing mechanism concept has allowed the introduction of five types of sensors. Because of this basic concept/principle, Wacoh has been successful (Okada 2001). Mr. Okada would start another company if he had another basic concept like this that he saw considerable future in.

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BACKGROUND

Waseda is a private university located on the outskirts of Tokyo. Professor Shoji moved to Waseda university seven years ago from Tohoko University in Sendai, where he worked in Prof. Esashi's research group. Professor Shoji's research program focuses biological and chemical applications of MEMS. The primary source of funding for his research group, of which Prof. Iwao Ohdomari is the head, is a five-year Center of Excellence award from the Japanese Ministry of Education and Culture (¥1.1B), which was initiated in June 2001. As a result of this award, a new fabrication facility to augment an extensive analytical laboratory capability and shared departmental clean room already in place is under construction.

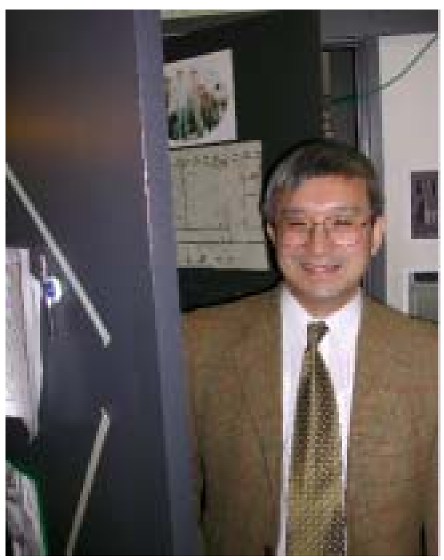

Figure B.24. Professor Shuichi Shoji standing in the doorway of a small coat closet that he has transformed into a highly compact and surprisingly effective fabrication facility. Space is at a premium at Waseda while a new state of the art fabrication facility is under construction.

RESEARCH OVERVIEW

One of Professor Shoji's areas of research is microfluidics using polymer, silicon, Teflon, and glass substrates. Teflon, which is somewhat unusual in MEMS applications, is deposited via spin-coating by Asahi Glass Company (the brand name is Cytop membrane). Professor Shoji has developed a microfluidic check-valve based on PDMS soft lithography. This development was presented in the most recent Micro Total Analysis Conference. Professor Shoji's group is developing a modular approach to enable system-on-chip ASIC-style fluidics. A library of building blocks of pumps, valves, reactors, separators, and sensors is being designed and tested. His group has also integrated an antibody array as a surface coating on a PDMS substrate, permitting high throughput antibody-based screening of biological fluids as they flow through a microchannel, primarily for protein detection applications. Professor Shoji is also interested in chemical synthesis applications. He is collaborating with professors Ikuta and Kitamori in this area, again to be based on the microfluidic building block library his group is developing.

Professor Shoji actively collaborates with Olympus in the bio-MEMS area. One collaborative project involves development of an on-chip bioreactor, essentially a PCR chamber on a chip. This effort is funded by the government's Bioinformatics Initiative (DNA analysis). Professor Shoji commented that Olympus seems to work with many universities on bio applications of MEMS. The head of the MEMS division of Olympus worked in Tohoko University previously and has decided to encourage such collaborations. Professor Shoji also presented a laser-driven valve being developed in collaboration with Olympus. The valve works through laser-based heating, which is used to trigger gelation of methyl cellulose, which in turn blocks a microchannel. The gelation is reversible by cooling, permitting the valve to be turned on and off repeatedly. When the gelation site is placed at a T-intersection, a multiplexor-style switch is formed.

A unique aspect of Waseda COE research involves single ion implantation to form nanostructures. A single ion is used to create localized damage to a surface. Scanning the ion beam creates an array of tightly spaced (a few nm) damage sites. Anisotropic etching is then used to create arrays of small pyramid-shaped tips. These tip arrays have potential application for ROM, biochemical, and biomedical applications. The single ion implantation equipment was developed locally by Prof. Ohdomari at Waseda University. This nanostructure effort is part of a university emphasis on wafer-level nanotechnology, i.e. electrochemical processing at a wafer level.

EDUCATION

MEMS/MST undergraduate and graduate level courses are both available in Waseda University. During the undergraduate course, Waseda provides an opportunity to develop a student project on a multi-project wafer, utilizing a service being set up through the IEE of Japan. This is not a foundry in the sense of MCNC-Cronos-JDS, but rather is a network of professors who request assistance from various companies they have relationships with, such as Yokagawa (for MEMS) and Olympus (for circuitry). Individual devices for a student project can be obtained at a cost of approximately ¥200K for 100 die ($20/die). Government support for this fabrication network has been requested but not yet funded. Historically, multichip fabrication has not been recognized by the government as valuable for education, although this may be changing now.

INDUSTRY INTERACTIONS

Professor Shoji's lab also brings in researchers from industry to learn micromachining in the university environment. Through collaborative projects with companies like Olympus and Shimazu (in the microfluidics area), industrial researchers gain experience with microsystems technologies. The university recently created a technology licensing office.

GOVERNMENT RESEARCH SUPPORT IN JAPAN

The WTEC panel discussed Japanese government support for microsystems research with Professor Shoji. Currently, the main focus of microsystems government research funding in Japan is nanotechnology, in part in response to the U.S. nanotechnology initiative launched by President Clinton. Other focus areas include biotechnology and environmental technology. In Japan, 'nanotechnology' historically means 'material science,' so involvement with MEMS and fabrication technology is a change. METI is very interested in MEMS applications for biochemistry and has an effort led by professors Kitamori and Shoji. The chemical industry in Japan is very interested in MEMS/MST. There is little government interest in RF and optical MEMS, although NTT does have an interest in optical MEMS research. Similarly, micropower generation is not a major focus in Japan, although it is a major focus area for DARPA in the United States. Professor Shoji indicated that the next large government project is most likely going to be MEMS for bio and chemical applications.

EQUIPMENT AND TOOLS

Professor Shoji's research group uses the Coventor design tools for microfluidics analysis and for surface micromachining simulations. An 80 square meter clean room (class 100), 160 and 180 square meter clean rooms (class 10000), facility is under construction. A single ion implanter, high resolution E-beam lithography, deep RIEs and fine electrochemical process equipment will be prepared in the facility. An extensive analysis capability is shared by the faculty, including multiple NMR scanners, AFM, TEM, STM, mass spectrography, and other test equipment.

U.S./JAPAN COLLABORATIONS

Professor Shoji feels that communication issues are an important factor limiting Japan/U.S. collaboration in the microsystems field. He recommends further exchange of professors giving talks between Japan and the United States to improve communication.

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Date visited: November 13, 2001

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Host: Professor Shigeru Ando, Department of Mathematical Engineering and Information Physics, Graduate School of Engineering, e-mail: ando@alab.t.u-tokyo.ac.jp

Also present:

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B. Mustapha—research associate from France

BACKGROUND

The Ando lab focuses on visual, auditory, and tactile sensing, approaching these problems from a system perspective. A particular strength of the lab lies in algorithms for processing and enhancing sensed data. Previous work includes processing video images and sound to extract 3-D position and motion as well as the developing robust tactile sensors.

RESEARCH ENVIRONMENT

The lab focuses on the entire sensing system. As such, MEMS technology is viewed as useful for subcomponents where miniaturization brings novel functionality. On a lean budget, the lab is adept at demonstrating innovative sensing principles using low-cost, hand-built apparatuses, many of which were exhibited to the panel in an impressive laboratory tour.

The high level of creativity can be partially attributed to the emphasis on a biomimetic approach. The group often looks to nature for inspiration on novel approaches to sensing or signal analysis.

Professor Ando cited a large gap between the device and system sides of MEMS. Monolithic on-chip integration of MEMS structures and associated circuitry is highly important. The primary motivation was the realization of large arrays of sensors with each element containing its own computational circuitry and actuation required for high-performance implementation of certain sense algorithms. Similarly, silicon is seen to be the dominant material due to its ease of integration with VLSI circuitry.

RESEARCH PROJECTS

Professor Ando explained that the human eye exhibits involuntary eye movement to provide a vibration used to extract a correlation signal. With this motivation, the group has developed a correlation image sensor in which the relative magnitude of the adjoining pixel is measured. Correlation in the time domain can also be measured. Coupled with a vibrating mirror (at 240 Hz), this system simulates the effect of involuntary eye movement and accomplishes real-time image processing such as edge detection. The correlation sensor can also be applied to ranging and spectral image matching. The latest sensing chip integrates the image sensors directly with the correlation processing circuitry, and the hope is to further integrate vibration actuators with the sensors as well.

B. Mustapha explained the tag-based machine vision project. Bar code tags are used to identify an object, followed by Internet retrieval of descriptor information related to the tag in order to allow the machine to have the most knowledgeable understanding of the sensed object.

Inspired by the human cochlea, the Fishbone sensor mechanically separates an audio signal into its frequency components. Used in conjunction with a logarithmic spiral reflector, this decomposition can be used to accomplish sound source localization. Used in reverse by actuating the “bone” fingers, the structure can be used to generate an impulse single. The cochlea has also been the inspiration for auditory scene analysis algorithms based on the decomposition of volume, pitch, and timbre. Finally, other types of direction-sensitive audio detectors have been demonstrated mimicking the ears of the barn owl and the fly.

The group has developed a number of robust tactile sensors that take various approaches to sensing the deformation of a layer of silicone that would be applied to the surface of the sensing appendage. The latest sensor principle achieves six-axis deformation sensing by launching ultrasonic waves from a 2 x 2 transmitter array and by measuring the waves with a similar receiver after they have traversed the medium.

Extending the work in tactile sensing, the group is now investigating methods for generating tactile feedback. In one device, a SAW device is used to modulate the stick-slip behavior of a slider on its surface. As the slider is pushed around by the user, the perceived surface roughness can be modulated by changing the SAW frequency. Another device launches ultrasonic waves at the user’s finger under water.

Dr. Shinoda also demonstrated an ultrasound emission device that utilizes the vibration from the heat exchange between porous silicon and the surrounding air.

LABORATORY FACILITIES

The laboratory facilities are limited, but nonetheless the group has been effective with limited funding. The MEMS fabrication of the fishbone sensor was done by Prof. Fujita’s lab and then later at Sumitomo, but the project no longer has funding to continue.

In place of expensive fabrication equipment, the group has proven to be highly adept at constructing prototype sensors by hand for proof-of-concept demonstrations. The barn owl ear sensor is built out of wood; and while it is rather large, the fly ear sensor consists of a 2 cm film with two poles, meticulously glued together by hand, providing the connection to the transducer below.

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Dave Visited: November 16, 2001

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Professor Fujita directs the Center for International Research on micro-mechatronics within the University of Tokyo Institute of Industrial Science. A unique feature of his work is a high degree of international collaboration, which is described in more detail below.

RESEARCH DIRECTION

The major research areas in Professor Fujita's group are optical MEMS and NEMS. A 3-D packaging system (see Figure B.25 below) that utilizes a micromachined wafer as a backplane for interconnecting electrical, optical, and mechanical microdevices to the external world has been developed. In this system, arrays of MEMS chips 'plug in' to a backplane using a V-groove-based latching mechanism. This packaging/assembly methodology has been demonstrated to achieve 10 micron alignment.

In the optical MEMS research area, a focus is on electromagnetic actuator development. An array of electromagnetic actuators is being used to construct an optical matrix switch. Magnetostrictive actuation (Terfenol-D TbDyCoFe alloy)is also being used to form a 2-D micro-optical scanner, in which both torsional and bending-mode vibration is induced in a mirror plate to achieve 2-D scanning of a reflected laser beam. The 2-D scanner is being supported by Renault-Nissan (a French-Japanese company) for collision-avoidance sensing. Additionally, a magnetically actuated optical scanner for an optical fiber diameter measurement system is being developed in collaboration with Gilbert Reyne and Hiroyuki Fujita of the Institute of Industrial Science at the University of Tokyo, supported by Anritsu Corp. Other projects underway include the development of MOEMS based on organic materials and the development of a III-V based tunable emitter at 1.3 um wavelength.

In the NEMS research area, projects include the following:

- Using a piezo-resistive probe for hole inner profile measurement
- Twin nano-probes for characterization of nano structures in TEM
- Micromachined STM for direct observation of atom transfer phenomena in a phase-detection TEM
- Magnetic STM with a non-magnetic tip
- Bio-microsystems for cells manipulation: application to the gene transfer
- Neural growth biomicrosystems
- Design and realization of a home-made robot for depositing pico-liter volumes of liquid

A multi-layer selective masking process has been developed to form multi-step structures (gears, pyramid, holes). This was presented in a poster at MEMS 2000. The process can also work from the back side of a wafer and may produce masters for use in PDMS-based soft lithography.

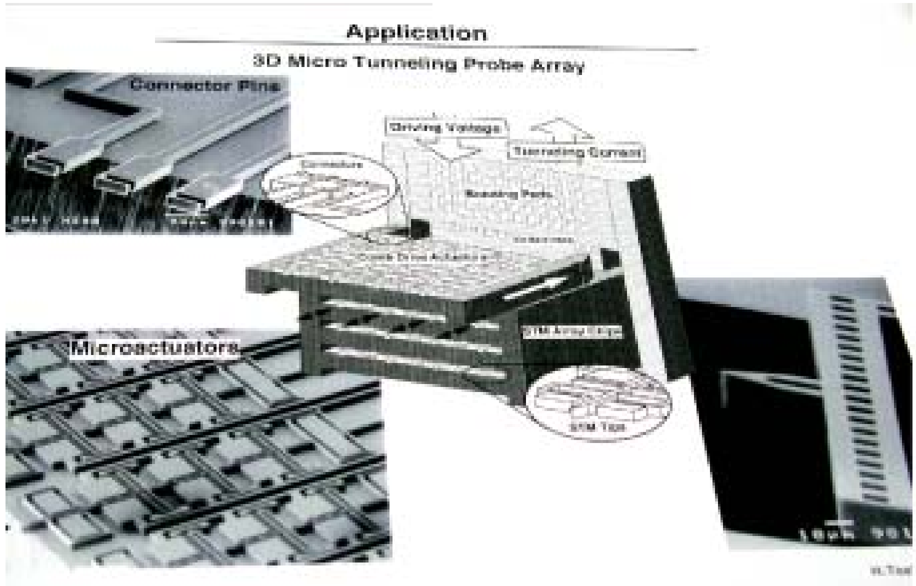


Figure B.25. Three-dimensional packaging of micro tunneling probe arrays using deep-RIE based alignment and interconnect technique.

International Program

A key distinguishing feature of Professor Fujita's work is its international flavor. As part of the Center for International Research on Micromechatronics (CIRMM), Professor Fujita operates a very active researcher exchange program with CNRS in France, as well as with other international institutions. Professor Fujita is personally involved in researcher exchange, spending between one and two weeks at a time in Paris four or five times a year. His laboratory maintains an office in Paris near the Eiffel Tower. Over the past six years, 35 researchers have visited Professor Fujita's group from abroad, participating in more than 30 joint projects and resulting in almost 200 publications and communications. A recent trend is that an increasing number of companies are becoming involved in the joint projects as well.

Enrollment in the University of Tokyo Electrical Engineering department is quite limited, and as a consequence Professor Fujita typically has only five or six students at a time. The international collaborations augment the research staff with 10-11 visitors, about half of whom are postdocs. Additionally, the lab has two permanent staff members who maintain the microfabrication facility. A small number of industrial visitors are part of the research group as well. For instance, Anritsu Co. currently has a researcher visiting the lab.

The CIRMM exchange program was funded by direct approval of the Japanese Diet in April 2000 for a period of 10 years. Professor Fujita feels that the exchange is of high educational value because it creates an international environment within Japan, providing even those students who do not travel overseas with an international experience—new ways of thinking and communicating—that would not otherwise be available.

Visitors to Professor Fujita's lab usually have technical backgrounds in optics or RF, not in MEMS, and are coming to the lab to learn micromachining. Visitors typically stay for two years, with a minimum commitment of one year. Student visitors receive a Ph.D. from France based on research work started in Japan, typically followed by one year of follow-up work in France. At present, approximately 10 visitors from France are in Professor Fujita's lab. Additionally, two postdoctoral fellows from Japan are working in France, supported by the French government with scholarships and a small research budget. Professor Fujita indicated that one of the biggest challenges in these collaborations is communication via the English language. English is a language that both the French and Japanese researchers have in common, yet neither party is a native speaker.

Intellectual property is handled in an interesting way. Postdocs own their own intellectual property as individuals. A professor can also write his own patent application. If a project uses national resources (not including student/postdoc support) in a substantial way, then a national patent application owned by the government must be written. Professor Fujita has found that it is necessary to have a patent when industry gets involved. For basic studies like nanotechnology one often needs to quickly publish and typically does not write patents.

FACILITIES AND FABRICATION NETWORK

Professor Fujita's group just moved into a newly constructed building about six months ago. Information on the new fabrication lab and its capabilities is available on the Web at http://fujita3.iis.u-tokyo.ac.jp/

DISCUSSION OF STATUS OF MEMS IN JAPAN

Professional Society

MEMS in Japan recently achieved a new milestone with the formation of a new IEE sub-society focused on sensors and micromachines. This society was founded by Dr. Isemi Igarashi, and the first president of the sub-society is Prof. Kiyoshi Takahashi. The new society's journal has 1500 subscribers, and 400-500 people attended the annual symposium. The sub-society includes three technical committees: physical sensors, chemical sensors, and micromachines and systems. Sixty percent of the papers in the journal and at the annual meeting are in English. Some members are from Korea—all are welcome regardless of nationality.

Foundry Service

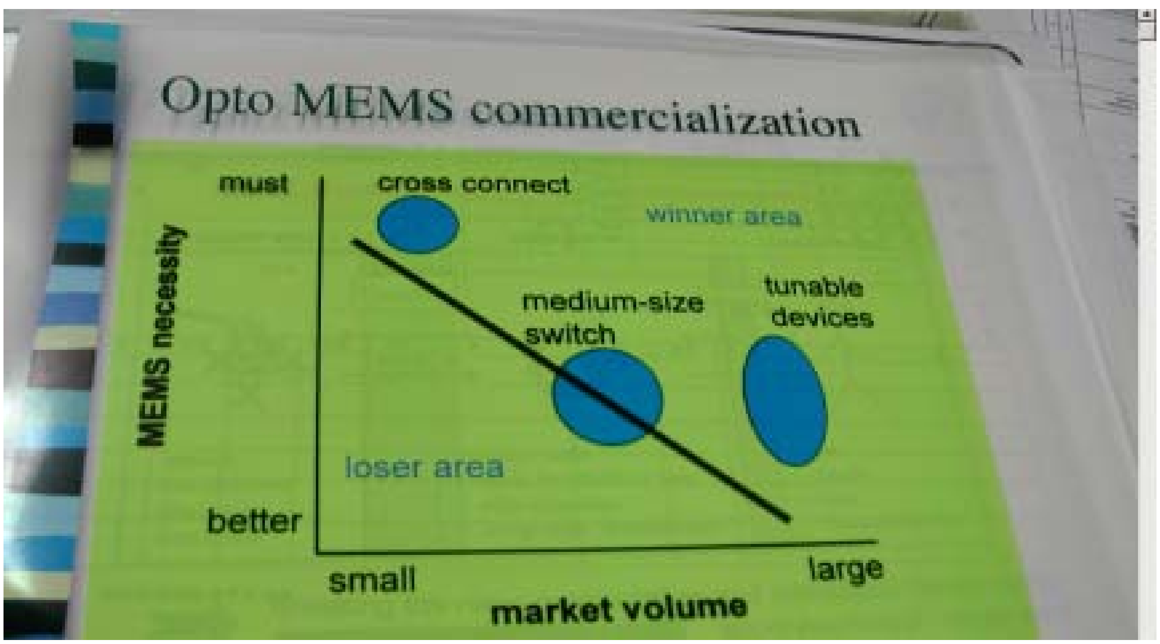


Figure B.26. MEMS commercialization issues. Professor Fujita views the role of commercial foundries to be lowering the slope of the line delineating the lower/winner boundary. In other words, making it easier for companies to enter the MEMS market successfully by reducing the risk level and costs associated with creating a captive foundry.

Professor Fujita is a strong proponent of creating a national MEMS foundry service in Japan, analogous to the MEMS exchange in the United States. Professor Fujita participates in an informal network, organized by Prof. Ikeda at Tokyo Agriculture University, that provides multi-project chips for educational purposes. The University of Tokyo's VLSI Design and Education Center (VDEC) has a mask-making machine. It takes about a day to make a 4-inch mask.

Professor Fujita observed that performance, rather than price, is now the key issue when MEMS technology is used. Without strict specification and requirements, it is difficult to choose MEMS for real problems. It may not be possible to find many large markets where MEMS is a necessity, as illustrated in Figure B.26. Many niche markets necessitate the foundry approach, in order to enable sharing of facilities. He views as positive the role of the Coventor and MEMS exchange in being the interface between application needs and manufacturing capabilities. In Japan, Sumitomo, Die-Nippon, Olympus, and Omron offer fabrication services, and TSMC in Taiwan is sometimes used as well. However, there is no organization to serve as the interface between the various foundries and the users. Professor Fujita sees the role of such an interface as critical because when multiple organizations contribute to fabrication of a component, reliability becomes a critical issue—which step in the fabrication process, i.e. which organization, is responsible? As a consequence, users are reluctant to use MEMS because there is no reliable set of foundry services, while foundries are reluctant to start because there are no users. Professor Fujita would like to push for this to create a boom for the field and is looking to the government to help make this happen.

What are the big obstacles to MEMS in Japan?

In research, there is a substantial need for resources beyond students' skills. In commercialization, there is also a need for foundry services, willingness for large companies to take risks, and willingness on the part of individuals to take the risk of forming a small company. Large companies have good researchers on MEMS, but the managers always ask about market size—one needs a huge market size to get attention from large players.

Government Research Funding Directions

The Japanese Micromachine Center efforts did not produce real products based on micromachines. There is no corresponding product to DARPA's DMD display and intertial sensors. However, commercialization was never a goal of the Micromachine Project. Ten years ago the metrics of success for research funding did not include commercialization, although that situation has changed today. The Micromachine Project did have a major impact, in effect establishing micromachines as a field unto itself—creating awareness that had a substantial impact on industry and that led to the creation of multiple industrial efforts that were not funded by the government.

In terms of government funding, Professor Fujita expects a long-term research funding program from METI, although this has not yet been announced. He expects the new program to focus on microchemical analysis and synthesis systems, as well as microfluidics, and he expects it to be funded at a level close to the Micromachine Project—perhaps a five-year program at half the level of the original Micromachine Project. Professor Kitamori is the key person working on this.

In conjunction with the automobile industry, there could be some micro-fuel-cell activities initiated in the future, but this is not a major focus area for government funding at this time. In contrast to the United States, RF MEMS is not a major national research focus at this time. There are some government-funded activities in the area of intelligent transportation systems (ITS) in which the sensor system is very important. Professor Fujita says, "If I hold a special session at a conference on ITS with MEMS, many people will come." This involves not only sensors, but also wireless communication, collision avoidance, and so forth.

There has been a major improvement in university facilities and equipment in the last 10 years. A couple of years ago, the government enacted a law to support basic science. The government has been supporting universities and research institutions, and there are many opportunities to have $1M level of projects which previously had been very difficult for a university professor to achieve. The funding model in Japan is different than in the United States. Grants do not pay for overhead or for students, so the bulk of the money goes to facilities. The Japanese Ministry of Education has a rule: you can't use more than 90% of your budget for facilities! This is in contrast to the United States, in which funding agencies generally will not pay at all for facilities, instead funding personnel.

APPENDIX C. MICROSYSTEMS RESEARCH IN THE UNITED STATES: A CRITICAL OVERVIEW[1]

INTRODUCTION

The field of microelectromechanical systems (MEMS) has developed rapidly since its beginnings in the 1980s, with a worldwide industry becoming well established by the year 2000. The range of MEMS applications has broadened from an early focus on silicon sensors for physical variables such as pressure and acceleration, to encompass a wide range of sensing and actuating functions. Over the past five years, the technology has matured to the point where the emphasis has shifted from device technology and design to the integration of sensing, actuating, computation, and communication into a *microsystem* that implements a useful function. The names of two major U.S. National Science Foundation (NSF) academic research centers reflect this shift in emphasis. The Berkeley Sensor & Actuator Center (BSAC), was originally called the Berkeley Integrated Sensor Center when founded in 1986 and was renamed in 1989 with the increasing importance of silicon actuator research. The Wireless Integrated Microsystems Center (WIMS), an NSF Engineering Research Center, was founded in 2000 and is led by the University of Michigan. Although much research on the scientific fundamentals of MEMS remains to be done and the level of maturity in device technology and design models is uneven across the wide range of applications, the future of both research and commercialization lies in the creation of microsystems.

Under the auspices of JTEC, Prof. Kensall Wise from the University of Michigan led a study of MEMS in Japan in 1994. The resulting report was widely circulated and had a significant impact on the research priorities of the NSF, one of the sponsors of the study. The 2001 WTEC Japan Microsystems Study is sponsored by the NSF, with additional support from the U.S. Defense Advanced Research Projects Agency (DARPA), the National Institute of Standards and Technology (NIST), and the Office of Naval Research (ONR). Both the MEMS and the microfluidic and molecular systems programs of the DARPA Microsystems Technology Office (MTO) are helping to support the study. The sponsors are interested broadly in defining the long-term research strategies for microsystems technologies, with a specific interest in the interface between the microsystems and nanotechnology fields. A sample of the microsystems applications of interest to the sponsors include the basic science foundation, bio-actuators, modeling the bio-electronic interface, microfluidics, bio-compatible microsystems materials, non-silicon microsystems fabrication, single molecule detection sensors, power issues in microsystems, wireless communications, optical communications, heterogeneous integration technologies, and self-assembly processes. Given the long-term perspective of this study, the sponsors are interested in new directions in both biological and physical microsystems research. Finally, the NSF is interested in Japanese activities in microsystems education and in encouraging interest in science and technology among pre-college students.

The panel members look forward to a vigorous interchange of ideas with Japanese researchers on the future of microsystems technology, which we are confident will prove to be of mutual benefit.

With the applications of microsystems in biology especially promising, we are interested in sharing perspectives on all aspects of this still largely unexplored area. Understanding the intersection between nanotechnology and microsystems technology in Japanese research strategy is a high priority. We would also like to understand the state of the infrastructure for microsystems research and development, including fabrication equipment, foundry services, design tools, and encapsulation processes. We also would like to discuss Japanese perspectives on the barriers to microsystems commercialization. Finally, the panel is interested in exploring areas where collaboration between Japanese and U.S. research efforts can prove fruitful.

[1] Prior to travelling to Japan, the WTEC panel members prepared the following summary of U.S. activities in Japan. This reflects the status in the United States as of the date it was completed, in October 2001.

In this report, we present an overview of the status of microsystems research and development in the United States, with an emphasis on emerging trends. Micro and nano fabrication technology, including materials, planar and 3-D processes, assembly, and integration processes are discussed first. Microsensors and microactuators continue to be a primary focus of academic and industrial research: we review research in biomimetic actuators, microactuators in wireless systems, optical switches, and fluid control. Progress in microsensors for physical, chemical, and biomolecules is described. Integrated circuits for sensing and control are also reviewed. The MEMS/microsystems industry in the United States has been volatile, with some areas experiencing consolidation. References to U.S. industry data are provided. Packaging and encapsulation technologies are surveyed—both are crucial to the success of microsystems and are receiving increasing industrial and academic attention in the United States of late.

MICRO AND NANO FABRICATION RESEARCH

Planar Process Technology

Radio frequency mechanical resonators and filters have motivated research on fabricating structures with lateral actuating gaps that are 100 nm or smaller—beyond the state of the art in optical lithography and etching processes. One approach is to use sacrificial layers defined by sidewall spacers (Hsu 2001), as shown in Fig. C.1. This resonator is the first MEMS micromechanical device capable of operation at 150 MHz with a *Q* approaching 10,000. The polysilicon disk is patterned by optical lithography, after which a conformal oxide film is defined that will later be etched. The oxide layer provides electrical isolation for the plating base for a nickel drive electrode. Although the sidewall technique is limited in its application, it will play an important role in the precise definition of offsets in micro/nano structures.

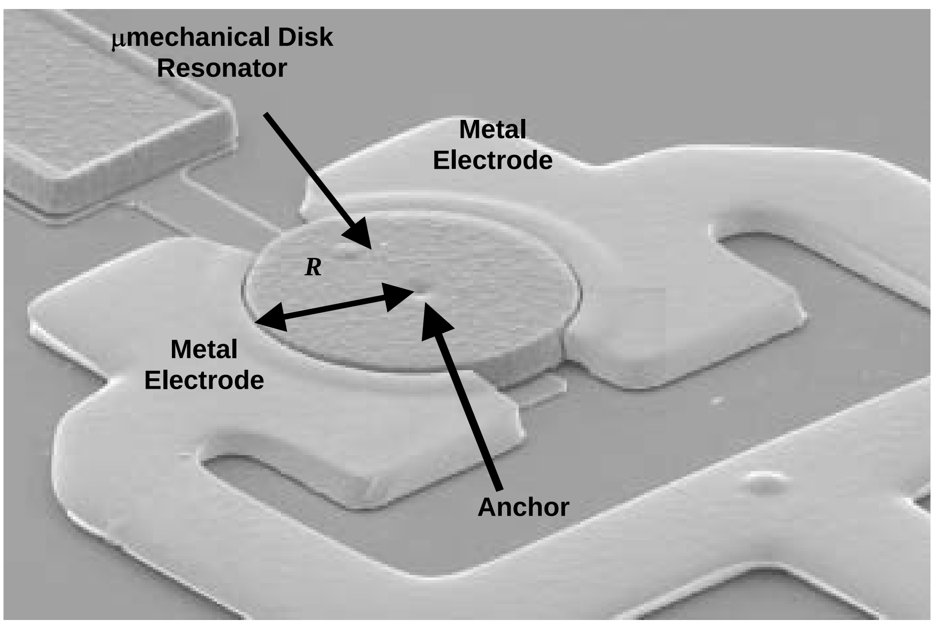


Figure C.1. SEM of a micromachined disc resonator with submicron gaps. This resonator is the first MEMS device capable of operation at 150 MHz with a Q approaching 10,000.

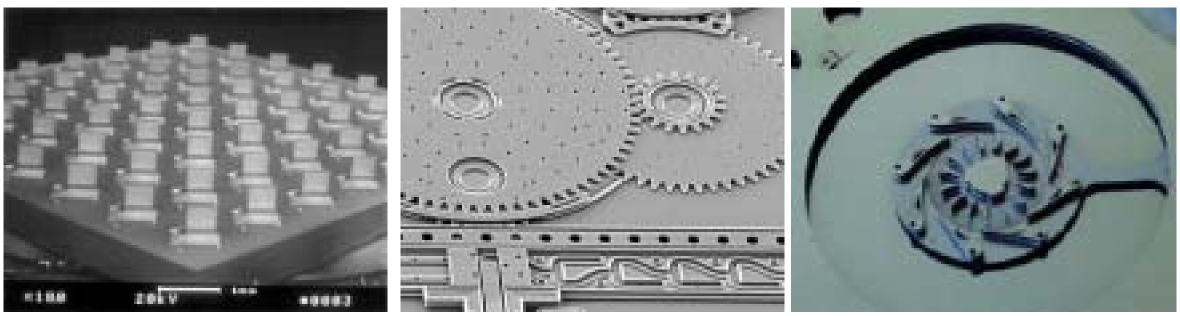
Many emerging applications also require the definition of fine features (< 1 μm) on devices for RF MEMS, bio-MEMS, high-density interconnects, and nano-mechanical systems. Many groups are using many of the standard submicron lithography techniques such as electron beams. However, e-beam lithography is still mostly a research tool that may not find its way to production too easily. As the integrated circuit (IC) industry develops deep-UV based lithography technologies for submicron IC manufacturing, these technologies are being increasingly used by the MEMS community to produce MEMS at reasonable cost. Therefore, it is expected that for the foreseeable future MEMS will continue to ride the wave of shrinking features that the IC industry has generated.

It is worth noting that one technology, namely focused ion beam (FIB) etching and deposition, is finding increasing use in MEMS and NEMS. Focused ion beams have been used for a long time by some in the IC industry for diagnostics and testing. The MEMS community has recently started to use this technique since it provides the capability to etch and deposit various materials with small and well-defined dimensions *in situ* without the need for lithography.

Three-Dimensional Micromachining Processes

The trend in the United States has been for 3-D micromachining strategies to be rooted in the existing expertise and momentum of planar surface micromachining. An early example of this was hinged surface micromachined structures, which have now found a marketable application in optical switching (Fig. C.2(a)). Numerous techniques have been developed to actuate these structures out of plane without manual manipulation.

The surface micromachining process itself has been extended up to five levels of polysilicon in the commercially available Sandia SUMMiT-V process (Fig. C.2(b)).



(a) (b) (c)

Figure C.2. Examples of 3-D MEMS: (a) 8 x 8 switching array of digital micromirrors from Optical Micro Machines, Inc. (b) Complex 3-D integration of planar parts in the SUMMiT-V process from Sandia National Labs. (c) The combustor and turbine elements of the MIT micro turbine engine.

More recently, Bosch deep-trench etching has dominated U.S. MEMS research. Although, most Bosch-etched structures have tended to be simply extruded versions of previous surface-micromachined designs, key advantages of the thicker designs are increased capacitance and mechanical rigidity. The latter benefit is particularly suitable for optical mirrors (Conant 2000). To achieve more truly 3-D structures from this technique, stacks of multiple wafers have been bonded. An extreme example of this is the MIT microturbine project (Figure C.2(c)), in which up to seven wafers are bonded at various stages of the process flow. Other techniques include multi-level Bosch etches in a single wafer, sometimes from both sides (Last *et al.* 2002), or serial assembly of Bosch-etched parts using mechanical interlocking connections (Zhou *et al.* 2002).

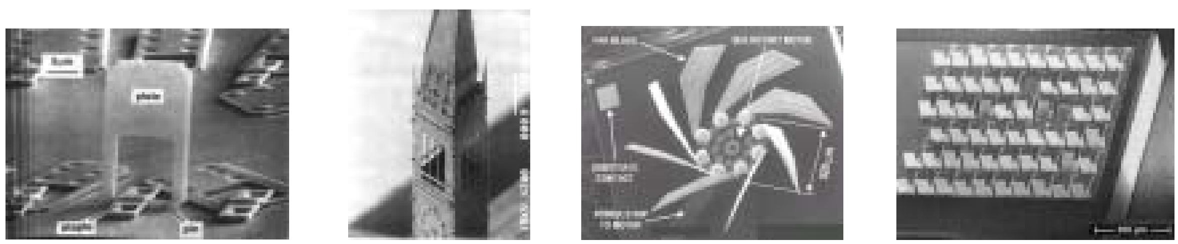
LIGA-like molding processes have seen comparatively less attention in the United States recently, in comparison to Bosch-etched silicon. Of note, however, is the great amount of attention given to molded polymers for biological microfluidics applications (Boone *et al.* 1998). Professor Stephen Quake at Caltech has achieved 3-D channel networks with integrated pumps and valves, using stacks of silicone elastomer simply molded off of photoresist (Unger *et al.*

In U.S. MEMS research, truly 3-D microstructures have not been the focus of much research, due to the reluctance of most research groups to pursue serial machining techniques or to utilize serial assembly. Momentum is beginning to build, however, in the use of batch assembly techniques, such as parallel transfer or stochastic self-assembly. Although the focus on batch processes could be viewed as restrictive, it may be argued that the resulting devices have been more amenable to low-cost mass production.

Parallel Assembly Processes

Through the 80s and early 90s, the United States favored a MEMS paradigm that emphasized batch processes and monolithic integration. From a manufacturing standpoint, it is very attractive to avoid serial assembly of system components, instead having all elements fabricated in place, as defined lithographically. However, the design space of systems that can be realized in such a manner is limited, particularly in the case of 3-D structures or the use of non-IC materials. In addition, a completely monolithic process may not be the most economically efficient. For example, one would not want to consume a large amount of die space in a high-performance CMOS process for use as a simple proof mass.

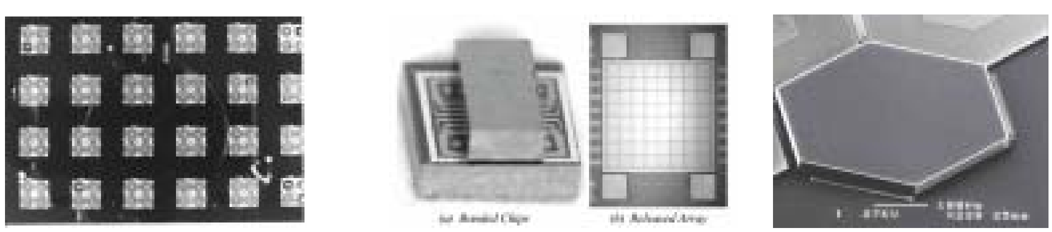
It is generally recognized that for many microsystems, some assembly is required. The desire for batch manufacturing remains, however; and so in recent years, there has been much U.S. research on parallel or self-assembly processes. Kris Pister showed that 3-D structures could be assembled from surface micromachined parts using hinges (Pister *et al.* 1992) (Fig. C.3(a)). The power of this technique to build complex structures is illustrated in the miniature model of the University of California, Berkeley, campanile clock tower (Hui *et al.* 2000) shown in Fig. C.3(b). This structure is a good example of design for assembly. The many elements, as fabricated, are arranged and constrained in such a manner that rotating a single element by 180° assembles the entire structure. Fold-up structures have been batch assembled, for example, using solder balls patterned on the structure (Kladitis *et al.* 2001) (Fig. C.3(c)) or with ultrasonic vibration (Kaajakari and Lal 2001) (Fig. C.3(d)).



(a) (b) (c) (d)

Figure C.3. Examples of assembled 3-D structures: (a) first hinged plate, (b) micro-scale model of Berkeley campanile clock tower, (c) reflowed solder balls used to self-assemble fan blades, and (d) batch assembly of fold-up mirrors by ultrasonic vibration.

Besides being used primarily to fabricate 3-D structures, assembly can also be used for the integration of parts involving dissimilar processes or materials. Such parallel assembly processes can be categorized as deterministic or stochastic. Deterministic assembly includes wafer-level (Singh *et al.* 1998) (Fig. C.4(a)) or chip-level (Michalicek and Bright 2001) (Fig. C.4(b)) transfer of pre-aligned structures on a donor wafer to the target, often using a gold compression bond.



(a) (b) (c)

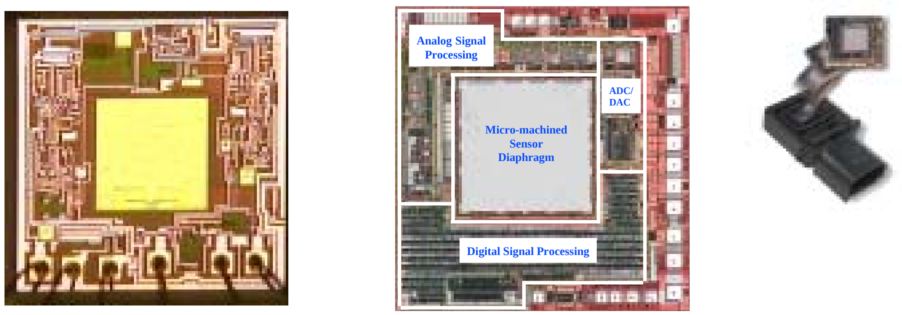
Figure C.4. Examples of assembly for integration: (a) wafer-level transfer of silicon actuators, (b) chip-to-chip transfer of mirror onto actuators, (c) capillary forces used to align mirror onto actuator.

Perhaps more groundbreaking has been progress toward stochastic assembly processes, in which parallel assembly is accomplished as an ensemble of randomly agitated parts moving towards a state of minimum potential energy. Yeh, Hadley, and Smith have accomplished fluidic self-assembly with trapezoidal parts being trapped in etched pits that defined gravitational potential wells (Hadley 1997; Yeh *et al.* 1994).

Through the patterning of self-assembled monolayers, potential wells from capillary forces have been applied for the assembly of bulk micromachined mirrors onto surface micromachined actuators (Srinivasan *et al.* 2000) (Fig. C.4(c)). In addition, stochastic assembly has been accomplished in a dry environment through the use of piezoelectric vibration, coupled with electrostatic potential wells (Bohringer *et al.* 1997), to break sticking forces.

MEMS/CMOS Integration Strategies

Circuit and MEMS integration has traditionally been one of the biggest debates in U.S. MEMS/MST technology. In fact, one of the Solid-State Sensor and Actuator Workshop (Hilton Head '98) "rump" sessions addressed this topic specifically. Cost is often the defining constraint; however, process flexibility, process capability, and time-to-market are all factors to be considered. Such factors are usually proprietary. Examples of integrated circuit + MEMS devices include the Motorola bulk micromachined bipolar or CMOS pressure sensors (Fig. C.5) and the Analog Devices surface micromachined biCMOS inertial sensor family (Fig. C.6).



(a) (b)

Figure C.5. Examples of (a) bipolar and (b) CMOS integrated bulk micromachined pressure sensors produced by Motorola (Ding *et al.* 1999).

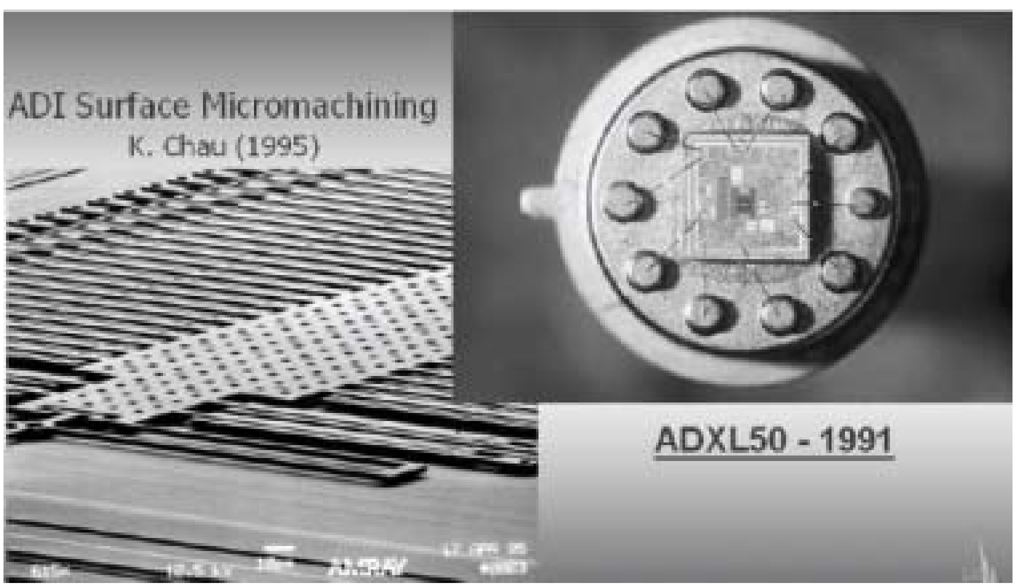


Figure C.6. An example of an integrated surface-micromachined, biCMOS accelerometer from Analog Devices.

A recent review of the various approaches to MEMS/CMOS integration appeared in the April 2001 *MRS Bulletin* (Franke *et al.* 2001). Recently, MEMSIC, Inc., has introduced a family of accelerometers that use post-CMOS micromachining processes to form thermally isolated structures suspended over a pit in the substrate. Integrated temperature-sensing circuitry detects the position of a plume of heated air that is sensitive to inertial forces. Since the electronics are fabricated prior to the micromachining steps, MEMSIC is able to use standard CMOS libraries for electronic design.

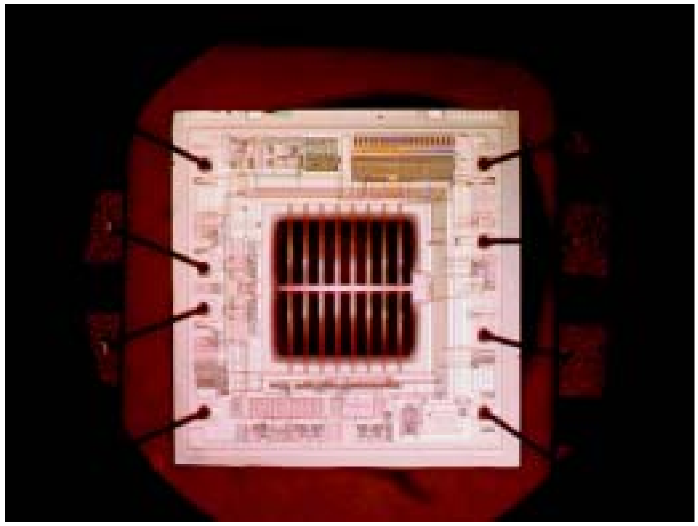


Figure C.7. MEMSIC MX-1010 one-axis accelerometer; courtesy of Dr. Yang Zhao, MEMSIC, Andover, Mass., www.memsic.com

Deep-reactive-ion-etching (DRIE) of the CMOS metallization-dielectric stack can also be used to fabricate micromechanical structures, as shown in Fig. C.8. Integration requires no modification of the CMOS technology, since all the micromachining steps are performed after its completion. This process is being made available on a multi-project chip basis through the ASIMPS foundry.

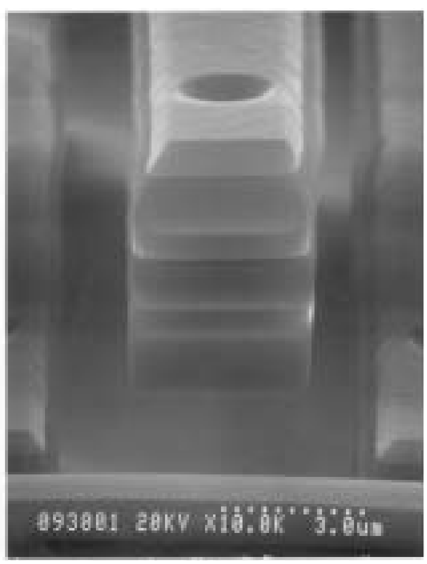


Figure C.8. Cross section of a multi-level metal microstructure fabricated by DRIE of the metal/interlayer dielectric stack; courtesy of Prof. Gary Fedder, Carnegie-Mellon University.

The possibility of stacking microstructures directly on top of CMOS interface electronics has been demonstrated by using low-temperature LPCVD poly-SiGe alloy layers as both the structural and sacrificial layers. Since hydrogen peroxide is used to remove the pure poly-Ge sacrificial layer, the CMOS layers do not need to be masked. In a recent Ph.D. thesis from Berkeley, a comb-drive resonator test structure was fabricated on top of its transresistance amplifier (Fig. C.9). This approach saves die area and also results in ultra-low parasitic vertical feedthroughs between the circuit and the microstructure.

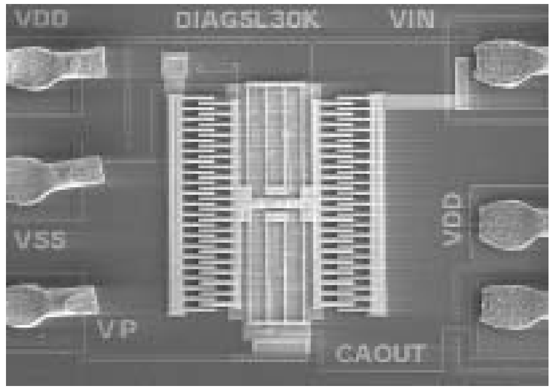
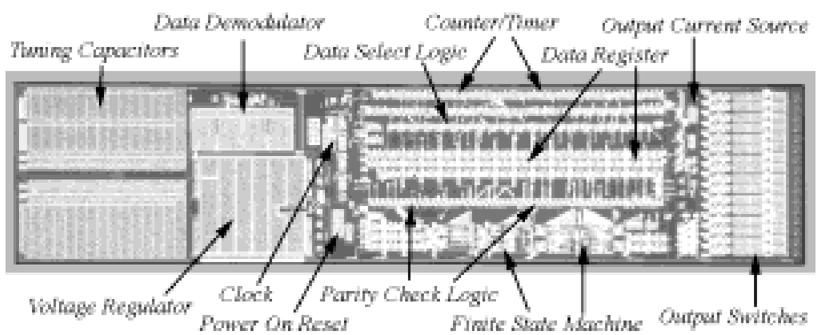
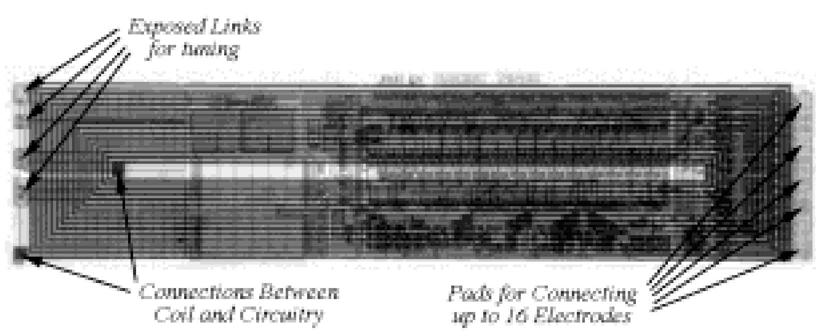


Figure C.9. Poly-SiGe comb-drive resonator fabricated over its CMOS interface amplifier (Franke *et al.* 2000).

Post-CMOS processing of electroplated metal structures is another powerful technology that has found application in areas such as automotive and biomedical devices. The attractive feature about this approach is that all processing steps are performed after the completion of CMOS fabrication, and all these steps are low-temperature and fully compatible with the CMOS process. The metallic MEMS structures are typically electroplated through a photoresist mask and can therefore be several tens to several hundred microns thick. Metals such as nickel, copper, and gold have been used. Copper is more attractive in RF applications where thick electroplated coils are used for making inductors or antennae. One of the most important and emerging applications of these coils is in wireless power and data transfer to MEMS chips. Figure C.10 shows micrographs of a BiCMOS chip with an on-chip coil (Von Arx and Najafi 1999). This implantable chip, developed at the University of Michigan, demonstrated one of the first applications of coil for wireless transfer of both data and power. The bottom photograph shows the BiCMOS chip with the coil integrated on top.



(a)



(b)

Figure C.10. Photographs of a BiCMOS chip with an on-chip coil: (a) the chip before integration of on-chip copper coil and (b) chip after fabrication of coil (Von Arx and Najafi 1999).

In addition to coils, electroplated post-CMOS MEMS have been developed for a number of applications. The first demonstration of this was the nickel vibrating ring gyroscope developed by Putty and Najafi (1994). This gyroscope was made of nickel electroplated on top of a CMOS wafer as shown in Figure C.11. Delco further developed the technologies needed for vacuum packaging the integrated sensor for automotive applications.

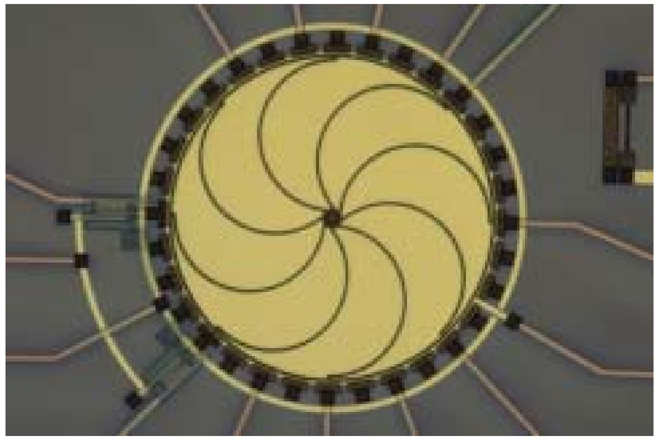


Figure C.11. Electroplated nickel vibrating ring gyroscope fabricated on top of a standard CMOS processed wafer (Putty and Najafi 1994).

Although in some applications full monolithic integration is desirable or required, in many applications—due to cost or process compatibility reasons—it is desirable to fabricate the MEMS and circuits on separate wafers and then flip-chip attach them at the wafer level in order to reduce the effects of parasitics, improve yield, and reduce cost. The first demonstration of this wafer-level chip transfer technology was demonstrated at U.C. Berkeley and was applied to hermetic packaging (Cohn *et al.* 1996). Other researchers have now expanded that technology to wafer-level transfer of MEMS dice onto circuit wafers. One of the best applications of this technology is in the emerging field of MEMS, and Nguyen's group at Michigan (Wong *et al.* 2001) has demonstrated the fabrication of a micromechanical resonator on top of a CMOS wafer through the wafer level transfer technology, as shown in Fig. C.12. This approach has the potential to reduce parasitics and to increase flexibility in utilizing different technologies for MEMS and circuit processing.

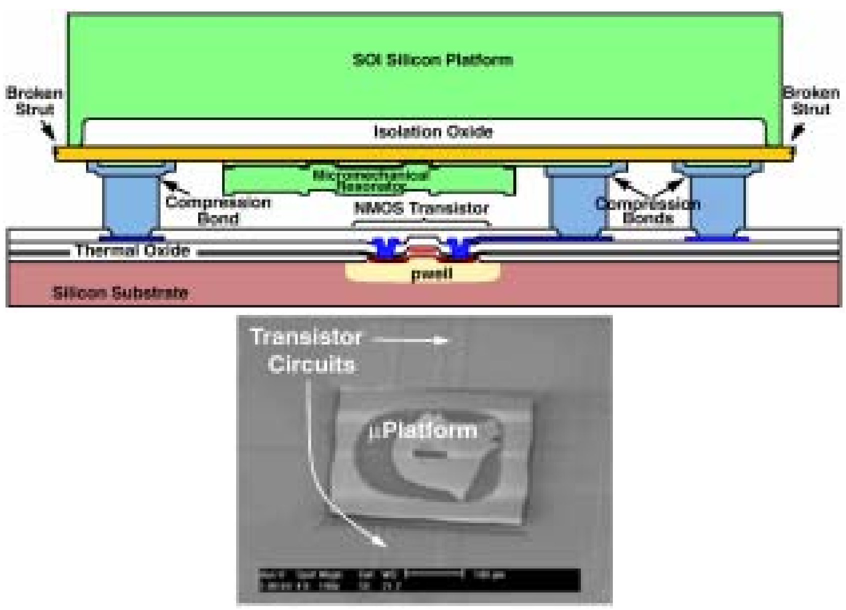


Figure C.12. Cross section and SEM of a microplatform containing a micromachined silicon resonator (the resonator is on the back side of the platform), bonded to a CMOS circuit wafer (Wong *et al.* 2001).

Finally, several full hybrid technologies that incorporate several chips inside a single package have also been demonstrated. Examples of multi-chip sensor devices include the Motorola surface micromachined "g-cell" in a "system-in-package" configuration with a CMOS interface IC (Fig. C.13).

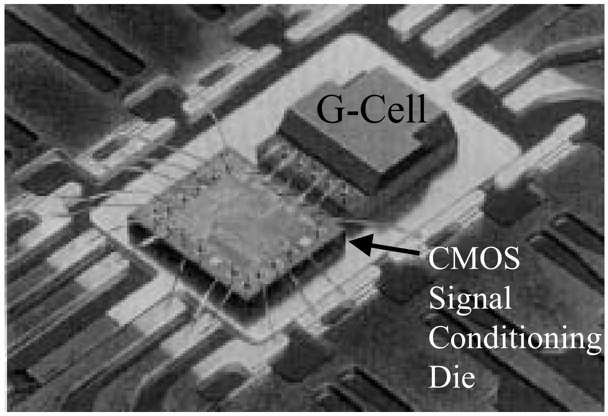


Figure C.13. An example of a non-integrated, "system-in-package" sensor that includes a surface micromachined accelerometer ("g-cell") chip-to-chip bonded to a CMOS ASIC. This accelerometer is produced by Motorola.

Furthermore, micromachined devices are movable structures, so there is effort to integrate some package functionality on chip. For example, the Motorola accelerometer family uses a glass-frit bonded wafer on the sensor die to minimize handling effects during assembly (Fig. C.13).

NANOFABRICATION

Government Support Activities

Advances in microlithography and nanolithography have enabled the fabrication of structures well into the deep nanometer regime. However, tools and methodologies to continually improve and shrink linewidths have been identified as crucial areas for U.S. investment. For example, DARPA and the NSF are expending significant sums to develop new technology for small-scale lithography. From the DARPA web site, the advanced lithography initiative (currently underway) states:

> The goal of the DARPA Advanced Lithography research program is to revolutionize semiconductor lithography technology through accelerated research of highly innovative technical approaches that will enable pattern transfer to wafers of features of 100 nm and below. …Innovative developments are targeted at tools and processes that are compatible with future manufacturing at exposure rates of one cm^2/sec. A variety of exposure sources offer sub 100 nm features, ranging from 157 nm optical to maskless approaches. The maskless efforts include electron, ion, and EUV (extreme ultraviolet). …Projection approaches include 157 nm, EUV, and electron, all at nominally 4:1 reduction, and proximity x-ray. …Research for these sources include architectural concepts, optics, unique mask technology, modeling, data handling, beam control, materials and characterization.
>
> Research in lithography support technologies addresses solutions applying to more than one source technology. Special areas of interest include mask technology (writing, inspection, repair, mask processing, and pellicles), generic resist technology (process development and control, etch selectivity, thinner layers, line edge roughness, and multilayer processing), inspection, and metrology (resolution, placement, throughput, modeling of defects, and characterization).

> Research in nanolithography technology addresses emerging devices, structures, and circuit functions that exploit features down to 10 nm and below. This includes tools or subsystems for patterning, materials, processing, 3-D device patterning, mask technology, modeling, characterization, and device demonstrations.

Additional investments into infrastructure include the U.S. National Nanofabrication Facility (NNUF), funded in large part by the NSF. The facility operates as a distributed user facility, with a distributed National Nanofabrication Users Network (NNUN), which can give users access to sophisticated nanofabrication technologies, without each user needing to acquire the capital-cost-intensive equipment that would otherwise be required to perform experimental research in this area. The NNUN is open to all users from academia, government, and industry. More from the NNUN:

> The combined staffs of the NNUN have extensive experience in all phases of nanofabrication and its use in fields ranging from nanophysics to biology to electronics. We have “domain experts” in micromechanics and biology to assist users in translating their ideas into experimental reality. With the assistance of the NNUN, users can often fabricate advanced nanostructures within weeks of initial contact. The NNUN also provides outreach support to the community through its Research Experience for Undergraduates program and training workshops. Our technologies are largely based on the thin film patterning techniques so successfully employed in the microelectronics industry. Extensive development and characterization within NNUN allows us to apply these same fabrication techniques to a wide range of materials and to diverse areas of science and technology. By working with NNUN, users gain access to extensive modern equipment and staff support.

In addition to the NNUN, the NSF is sponsoring a variety of programs to develop nanotechnology. The goal of these programs is as follows:

> to support fundamental research and catalyze synergistic science and engineering research and education in emerging areas of nanoscale science and technology, including biosystems at the nanoscale; nanoscale structures, novel phenomena, and quantum control; device and system architecture; design tools and nanosystems specific software; nanoscale processes in the environment; multi-scale, multi-phenomena modeling and simulation at the nanoscale; manufacturing processes at the nanoscale; and studies on the societal implications of nanoscale science and engineering.

In particular, there is currently a competition for ‘NIRTs’ and ‘NERs’. Nanoscale Interdisciplinary Research Teams (NIRTs) are teams of 3-5 people from various disciplines to work together for 3-5 years on an interdisciplinary nanotechnology project. Nanoscale Exploratory Research (NERs) are typically one-year, one- or two-investigator seed programs, that allow the investigation of new nanoscale phenomena prior to investment in a full research program.

The U.S. Army Research Office (ARO) is planning substantial funding in the area of nanofabrication through the Center of Research for Nanoscience for the Soldier. This program is currently in the stages of inviting proposals to be submitted, with awards to be announced at the end of 2002. The purpose is to create a

> University Affiliated Research Center (UARC) to develop nanometer-scale science and technology solutions for the soldier. A single university, along with industry partners, will host this center to emphasize revolutionary materials research toward an advanced uniform and protective ensemble concept. <…> Through this competition, the ARO expects to award a single non-fee-bearing contract having an initial performance period of five years and an estimated base cost of $50,000,000. <…> The resulting contract will include provisions for task orders for additional effort estimated to reach $20,000,000 over the five-year term.

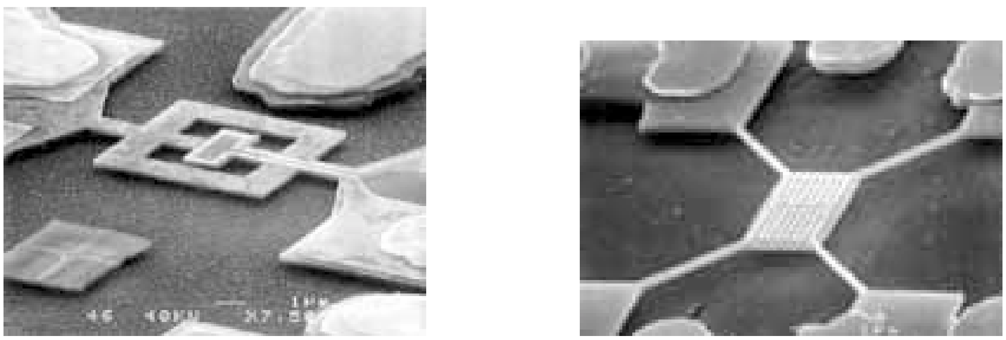
In addition to tool and infrastructure development programs, the government is also funding application-driven research. As just one example of many, DARPA is currently funding a program on ‘Nano-

Mechanical Array Signal Processors' (NMASP). The goal of this program is to demonstrate arrays of nano-precision high-Quality-factor (Q on the order of 10,000) ultra-high frequency (UHF) (300 MHz to 3 GHz) mechanical resonators that will achieve radical reductions in size and power consumption over state-of-the-art RF transceivers and signal processors.

Research

Research in this area can loosely be divided into two approaches: the *top-down* approach, in which conventional MEMS techniques are extended into smaller and smaller realms, and the *bottom-up* approach, in which chemistry and self-assembly are utilized to fabricate microstructures. Although an exhaustive listing of the research programs being pursued are beyond the scope of this document, some highlights from both the top-down and bottom-up approaches are given below.

Top-down approaches are being pursued by a variety of researchers, including most notably Roukes at the California Institute of Technology and Craighead at Harvard University. Roukes has pioneered this area with nanoresonators (Fig. C.14(a)) and thermal quantization devices (Fig. C.14(b)).



(a) (b)

Figure C.14. Nanostructure devices by Roukes at Caltech: (a) nanoresonator; (b) thermal quantization device

These approaches are also being used by researchers at the NNUF. For example, Figure C.15 shows a silicon device made by Cornell University researchers consisting of a "paddle" three micrometers in size (center) supported by beams 170 nanometers wide.

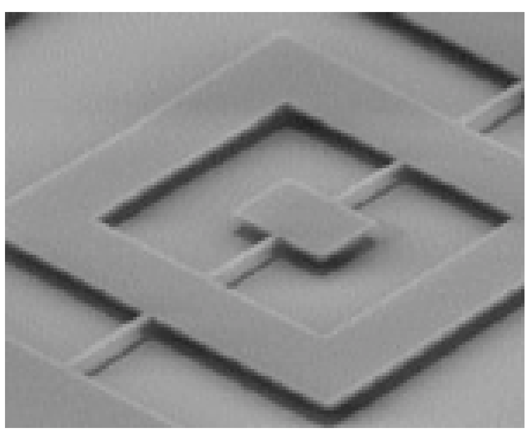


Figure C.15. Silicon paddle from Cornell. The supporting beams are 170 nm wide.

These devices were fabricated using extensions of traditional lithography, such as electron-beam approaches. However, IBM is utilizing different tools to fabricate nanostructures. For example, the IBM-Watson Research Center is utilizing scanning tunneling microscopy (STM) and atomic force microscopy (AFM) as structural probes, and, along with electron beam lithography, as tools for the modification of materials at the atomic and nanometer scales and the fabrication and study of nano-electronic devices. Currently, IBM researchers are investigating carbon nanotubes, nanolithography, and silicon nanoelectronics, with an eye toward ultraminiature electronic devices and extremely-high-density data storage. As just one example of the types of methodologies that can be employed, IBM researchers are employing nanometer-scale local oxidation of semiconductors and thin metal films and its use for the fabrication of novel electronic devices. Figure C.16 shows an AFM image where oxide lines about 20 nm in width were used to define the silicon dioxide pattern "IBM NANO" on a silicon wafer. They use a negatively biased AFM tip in the contact mode to write 10-100 nm thin oxide lines in semiconductors and metals. In addition, they can employ high lateral current densities in thin metal films to form 10-50 nm thin oxide barriers.

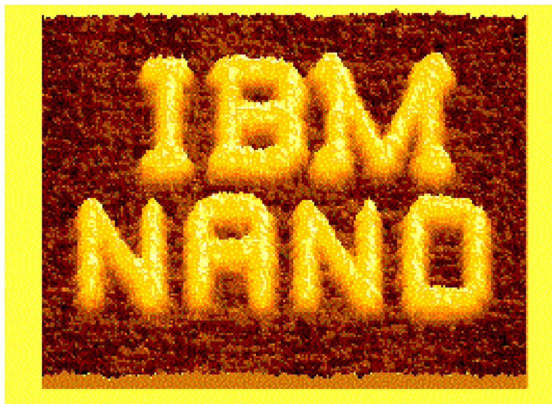


Figure C.16. AFM image of 20-nm oxide lines spelling "IBM NANO".

Although it is not being carried out in the United States, much of IBM's data storage work is occurring in the Zurich research facility in Switzerland and is relevant to this report. The so-called "Millipede" concept (Fig. C.17) suggests the feasibility of a high-density data storage system based on micromechanical components borrowed from AFM: tiny depressions melted by an AFM tip into a polymer medium represent stored data bits that can then be read by the same tip. This thermomechanical storage technique is capable of achieving data densities in the hundreds of Gb per square inch range, well beyond the expected limits for magnetic recording (60–70 Gb/square inch). Whereas the readback rate of an individual probe is limited, high data rates can be achieved through the use of massive parallelism: in the Millipede system concept, the read/write head consists of an array of more than 1000 thermomechanical probes, fabricated on a single silicon chip using VLSI microfabrication techniques that operate simultaneously.

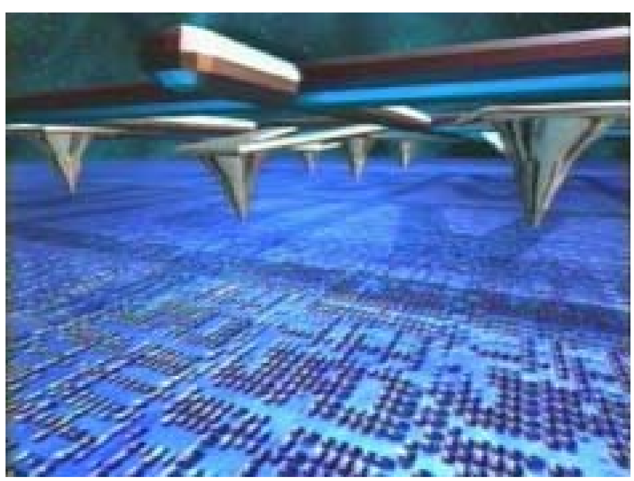


Figure C.17. Millipede thermomechanical data storage system.

Bottom-Up Approaches are primarily being undertaken from the realm of chemistry. Lithography is typically used to define chemically-active regions on a surface, followed by sequential immersion in appropriate chemical solutions to grow self-assembled monolayers on the patterned surfaces. Both traditional lithography (including that used to manufacture structures as shown in the previous section) as well as so-called 'soft lithography' can be used prior to self-assembly.

Soft lithography represents an alternative set of techniques for fabricating micro and nano structures. The original version of this technology, pioneered by the Whitesides group at Harvard University, employed an elastomeric stamp (or mold) to pattern a wide variety of materials such as self-assembled monolayers (SAMs), organic polymers, colloids, inorganic solids, proteins, and cells. The technology is now widely utilized in applications ranging from bioanalysis chip preparation to catalyst deposition. Figure C.18, from the Whitesides group, shows structures as small as 80 nm patterned using soft lithography approaches.

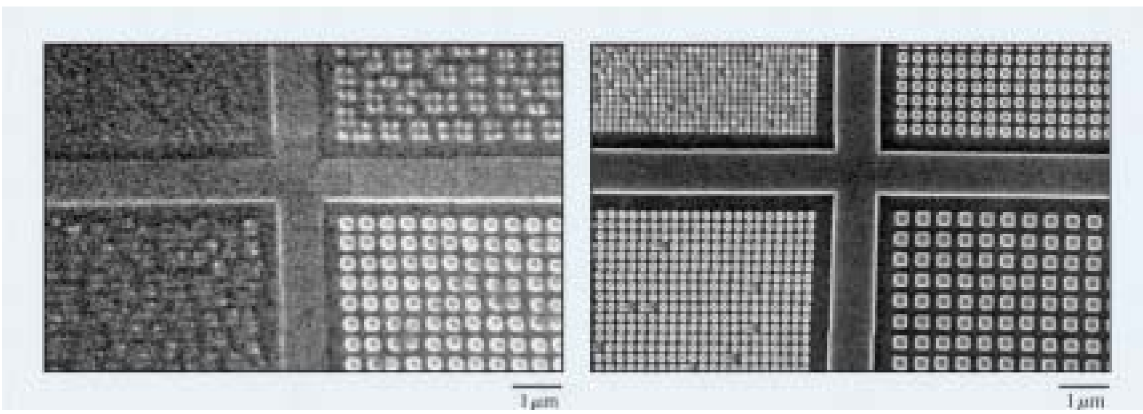


Figure C.18. Nanostructures patterned by soft lithography. (Whitesides group)

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MICROSENSORS AND MICROACTUATORS

The authors wish to thank S. Sibbett and M. Dierks for contributions to this section

MEMS Transduction Mechanisms

MEMS activities in the United States for the most part have evolved from a background of semiconductor wafer processing, but have broadened over time to include meso-scale devices and non-silicon fabrication techniques such as soft lithography and hot embossing.

Some of the primary transduction mechanisms are listed in Table C.1

Table C.1
Primary Transduction Mechanisms

Transduction Mechanism	Typical applications
Actuation mechanisms	
Electrostatic attraction	Tilting of planar structural elements, such as optical mirrors; actuation of comb drives
Comb drive actuators	Linear oscillatory motion control
Polymeric actuation (phase-change based; poly-vinyl alcohol)	Artificial muscles
Magnetic actuation (external magnet applying force to on-chip coil)	Steerable mirrors; aircraft turbulence and maneuvering control
Pneumatic	Microfluidic pumping and valving; levitating object transports
Hydraulic	Microfluidic pumping; injection nozzles for mass spectrometry
Acoustic	Mixing; inkjet printers; MEMS hearing aid speakers
Thermal (phase change)	Inkjet printers; bio-MEMS (PCR reaction chambers)
Electrokinetic	Protein separation chips, microfluidics
Thermal (bimorph bending and/or induced buckling)	Steerable beams
Sensing Mechanisms	
Deformable optical gratings	Switch between reflection and refraction. Used as both an actuator for displays and as a sensor for vibrating beams, Honeywell's optical polychromator, etc.
Piezoresistive	Typically used for polysilicon devices
Capacitive	Accelerometers, etc.
Chemical	Electronic nose
Acoustic	Directional MEMS microphones
Biological	DNA arrays; antibody arrays; protein separation chips
Pressure-based	Deformable membranes detecting via optical beam, piezoresistivity, or capacitive sensing.
Resonators	
FBAR	Thin-film bulk acoustic resonators—used in RF MEMS applications as both actuator and sensor. Potential for up to ~10 GHz frequency range
Cantilever NEMS	Up to 1 Ghz frequency range
Suspensions	Accelerometers, etc.
Rotating machinery	Microturbines, rotary motors, etc.

Transduction Mechanism Close-up: Chemical Sensors

Fundamental mechanisms for the detection and quantification of chemicals are based on transduction mechanisms converting the chemical or its presence by detectable "signatures" into some form of usable and recordable signal, *e.g.*, optical absorption and reflections, specific chemical affinity, frequency shift/refractions, chemical reactions mediated, inhibited, or modulated by the chemical to be detected, *etc.*

Chemical sensors are devices that detect the presence or quantify the concentration of a family of chemicals or a specific chemical exposed to the sensor. The sensor will rely on one or multiple sensing mechanisms and produce a signal that indicates the presence of the chemical and/or its concentration. Types of chemical sensors include electrochemical sensors, gas sensors, mass sensors, thermal/calorimetric sensors, optical sensors, biosensors (detection raging from single biomolecules, multi-molecular compounds, components of organella or cells and tissues), *etc.* Different sensors operate in different phases of materials, *e.g.*, vapor/gas, liquid, sol-gel, and solid, *etc.* for specific applications.

Typical MEMS chemical sensors are based on "active" chemical sensing elements interfaced and packed on a micromachined chip attached to the ceramic substrate. For example, a MEMS chemical gas sensor based on a polymer-based chemical gas sensor array on silicon is shown in Fig. C.19 (Zee and Judy 2001).

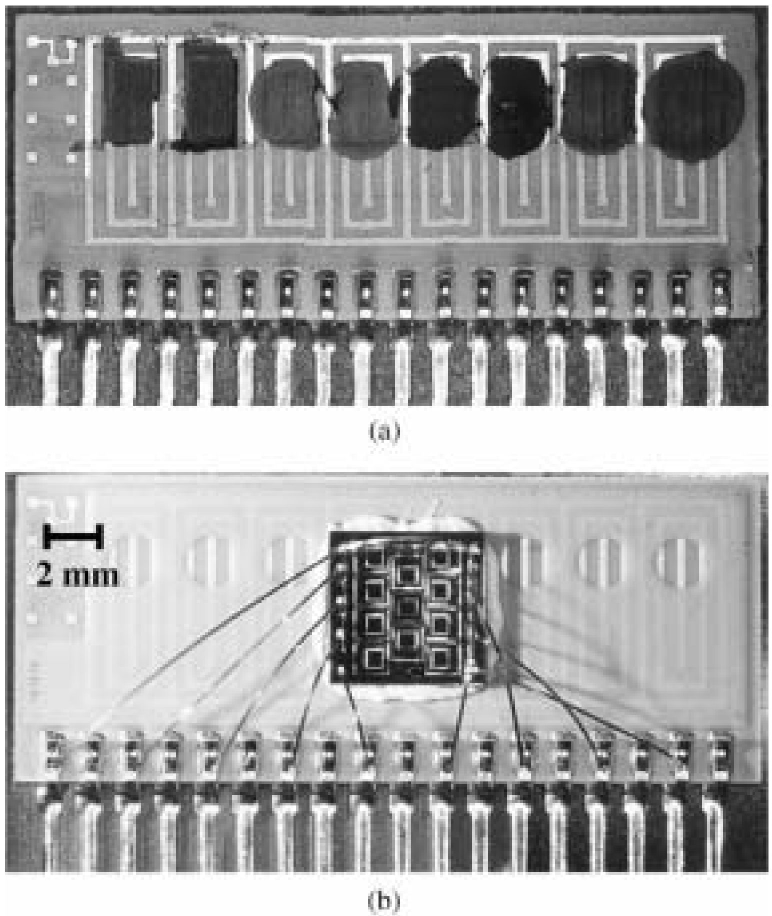

Figure C.19. Micrograph of polymer-based chemical gas sensor array (Zee and Judy 2001).

Professor M.J. Sailor of U.C. San Diego and his group is developing nanostructured sensor-based detectors for high-throughput detection applications such as DNA diagnostics, drug discovery, label-free detection of antibodies, etc. These are different from polymer-based sensors. They are also developing aqueous-phase sensors for toxins and other environmental hazards and gas-phase sensors with applications in detectors for chemical warfare agents, classifiers for odorants, and monitors for air quality. They mostly use silicon nanocrystallites or nanowires. Recent work in this area has focused on two types of sensor devices: photoluminescence from the quantum confined nanocrystallites of Si and optical interferometry on thin Fabry-Perot layers of porous Si. Their luminescence energy transfer studies have led to the discovery of a detector for the explosive TNT and dinitrotoluene at the ppb level. Demonstration of detection of physisorbed molecules by luminescence quenching led to a general-purpose vapor detector that was developed in conjunction with the company AlphaMOS America. The thin-film studies led to the discovery of a sensitive biosensor that consists of a thin layer of a chemically modified silicon film.

Figure C.20. A handprint containing trace amounts of TNT—produced by placing a tenth of a gram of TNT on a latex glove, then wiping the glove clean—shows up as a darkened silhouette of the hand. A similar handprint without TNT has no effect on the flat, greenish glowing paper.

Figure C.21. Polysilole nanowires used to image a TNT-contaminated thumbprint on a transit ticket from the San Francisco BART subway. The ticket on the left is the control. Both tickets were treated with the nanowires to develop the latent image of the thumbprint after it had been held in a contaminated hand.

Among the chemical sensors, so-called "electronic noses" or "artificial noses," are based on MEMS chemical sensors. AlphaMOS America (http://www.alpha-mos.com/proframe.htm) was one of the first companies to introduce electronic noses to the market. The first generation of e-nose was based on sensor arrays (with different types of sensors); and in 1999 AlphaMOS launched a new type of electronic nose based on fingerprint mass spectrometry. Multi Organoleptic Systems (MOS) technology has recently been developed for the digitalization of both smell and taste. Today, many industries rely on human panels or on analytic techniques (e.g., gas or liquid chromatography) to evaluate products whose odor or taste characteristics are key to customer acceptance. Both methodologies have shown to have some major drawbacks: Human sensorial methods are amazingly accurate, but people fatigue easily and are somewhat subjective in their evaluation. They are not always as consistent as we would like and transferability from one person to another is extremely difficult. Furthermore, classical techniques such as chromatography are precise and objective but relate only to specific parts of smell or taste, and not always to the part considered most significant by the human senses. Moreover, skilled technicians are needed to interpret the data.

To overcome these drawbacks, smart sensing technologies are considered a viable alternative to routinely distinguish differences, predict acceptability of odors and volatile organic compounds (VOCs) from a large range of raw materials and intermediate and finished products. Applications may begin as early as the crop-growing stage (to test the maturity, contamination of molds, parasites), may cover harvesting and the reception of incoming raw materials, control the process, inspect the finished product, and test for package tainting of the product. Applications also exist at the distribution level to check that the products received meet specifications.

Other applications include monitoring gas emission levels from factories or intensive livestock farming zones, water systems, and even subway stations. The Paris transport authority (RATP) uses an instrument on trial at the Saint-Augustin underground station. The defense and security industries are interested in the possibility of detecting anti-personnel mines, gases, and drugs. Applications here could include tracking down drugs or explosives in airports. Research is under way in Germany into the identification of criminals using body odors. A promising market would be where the technology could be used to identify, and even quantify, bacterial organisms. Speed of detection and analysis are the key requirements. Applications include the detection of listeria and salmonella in the food industry. In the medical field, the electronic nose can be used to monitor the progress of respiratory or digestive track conditions in both human and animal subjects, for ulcer monitoring or urine analysis. The system's key advantage, yet again, is its ease of use, which makes testing simple and cost effective.

The Electronic Nose (ENOSE) is a device that is being developed at the Jet Propulsion Laboratory (JPL) and the California Institute of Technology (Caltech – http://www.micro.caltech.edu/micro/research/electronic_nose.html). In many ways, it mimics the human nose and is designed to monitor changes in an atmosphere to which it is exposed. This work, inspired by the human olfactory system, originated as a result of research advances made by Prof. Nathan S. Lewis of Caltech.

The ENOSE consists of an array of different polymeric thin-film sensors that have been shown to respond to a number of organic and inorganic compounds in the parts per million (ppm) range. It is based on the multi-sensing principle, in which the distributed response of an array is used to identify the constituents of a gaseous environment. Individual sensor films are not specific to any one gas; it is in the use of an array of different sensor films that gases and gas mixtures can be uniquely identified by the pattern of measured electrical response.

Currently under development is an experimental instrument to monitor the air quality on the Space Shuttle. Twelve compounds that have been detected on the Space Shuttle have been targeted for sensing on the first validation experiment. The instrument consists of an array of up to 32 polymers that are deposited on four small 10 x 25.4 mm ceramic substrates. Each deposited polymer creates a sensing film of about 2 mm on the side and a few microns thick. The sensor substrates are in a sealed enclosure less than 15 cm^3 in volume with provisions for letting sample air in and out. Air flow is assisted by a small pump (about 2 liters per minute). There are two air inlet paths. One path is through a small activated charcoal filter that is used periodically to establish a baseline for the sensor. The other path is not filtered and is used to pump the sampled air through the sensor enclosure. Switching between these paths is accomplished by solenoid valves under microprocessor (program) control. The polymer sensor response to gases is detected electronically by measuring changes in electrical conductivity. The data are then analyzed by a neural net pattern recognition software engine that deconvolutes the data to identify the sensed compounds and their concentrations. For the planned STS 91 Shuttle validation experiment, there will be no on-board data processing. Data collected during flight will be stored in memory and brought back for post-flight analysis. For this experiment, the instrument weighs about 1.8 kg and is in a single enclosure 11.4 x 22.8 x 9 cm. JPL researchers are looking at coming generations that will reduce the instrument to credit-card size.

As electronic noses are carried into the future, the applications for these products will grow. Future electronic noses may be applied to environmental problems such as analyzing hazardous waste, fuel mixtures, ground water, air quality, or factory emissions. The food industry is already using these mechanical sniffers, but the uses could grow to include fish inspection, fermentation processes, container examinations, or verifying whether orange juice is "natural." The electronic nose could even be used in telemedicine so a doctor would be able to smell the breath of a patient a thousand miles away by recreating what an electronic nose smells. Someday household refrigerators may alert the owners to the potato salad that has been left in the fridge since last Christmas. Eventually, many questions concerning the human olfactory system will be answered, and perhaps artificial solutions will be found for people with olfactory problems.

Interface Electronics

Electronics is finding increasing applications in many areas of MEMS and microsystems. The traditional role of electronics in MEMS has been as interface circuits for both sensors and actuators. However, as sensor technologies have matured and as MEMS are finding their way into true microsystems that require not only sensors and actuators to interface with the outside world, but also sufficient signal processing capability to process transducer information and make intelligent decisions, we have seen the emergence of chips that include both interface circuitry for transducers and digital electronics for control and signal processing applications. The general architecture of a wireless microsystem is shown in Figure C.21 (Wise *et al.* 2001). External physical and chemical parameters are measured and converted into an electrical format using an array of sensors. The sensed data are collected, processed, and digitized using in-module (integrated or hybrid) circuitry and are transmitted over a digital bus to a host controller. The host controller uses this information to make appropriate decisions and feeds control information back to the external environment through an array of actuators.

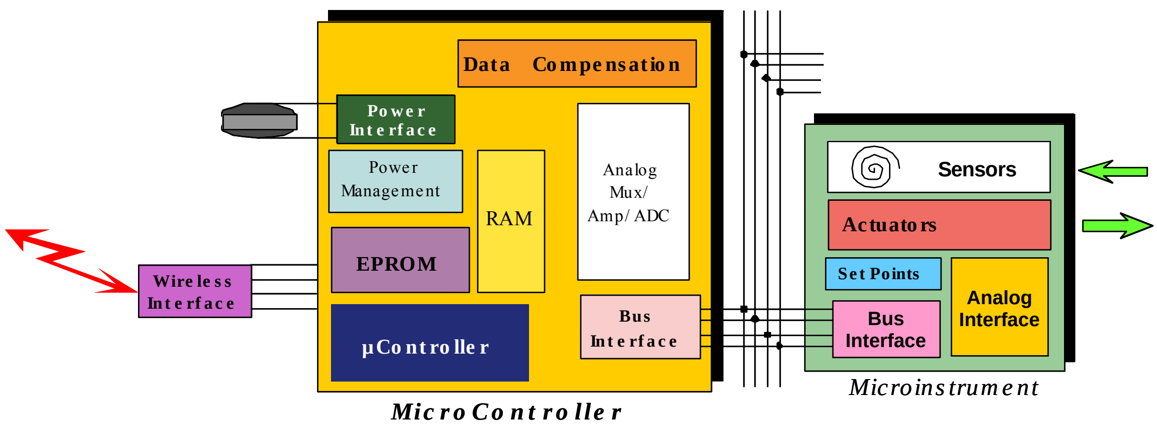

Figure C.21. The general architecture of an instrumentation system (Wise *et al.* 2001).

Such systems are increasingly needed in many applications, including automotive, health care, manufacturing, environmental monitoring, industrial processing, avionics, and defense. For many applications, it is absolutely required that the overall system be as small as possible, use low power, and have a reliable wireless communication link. Several groups in the United States are currently working on the development of these systems, including groups at the University of Michigan where a new Center on Wireless Integrated Microsystems (WIMS) (http://www.eecs.umich.edu/WIMS) was recently funded by the National Science Foundation, and at the University of California at Berkeley, where work has been ongoing on the development of miniature sensing modules referred to as “smart dust” (Warneke *et al.* 2001).

Figure C.22 shows one such wireless microinstrumentation system where a number of sensors such as pressure, acceleration, temperature, and humidity have been incorporated into a wearable module (about 7 cm long and 3.5 cm wide) that includes a microcontroller and a wireless RF link with a range of about 50 m Mason *et al.* 1998). Figure C.23 shows the photograph of an early version of a “smart dust” system that includes the battery and other chips for sensing temperature. These smart dust motes use an optical link for communicating information back to a host controller.

Figure C.22. A wearable wireless microinstrumentation system (Mason *et al*. 1998).

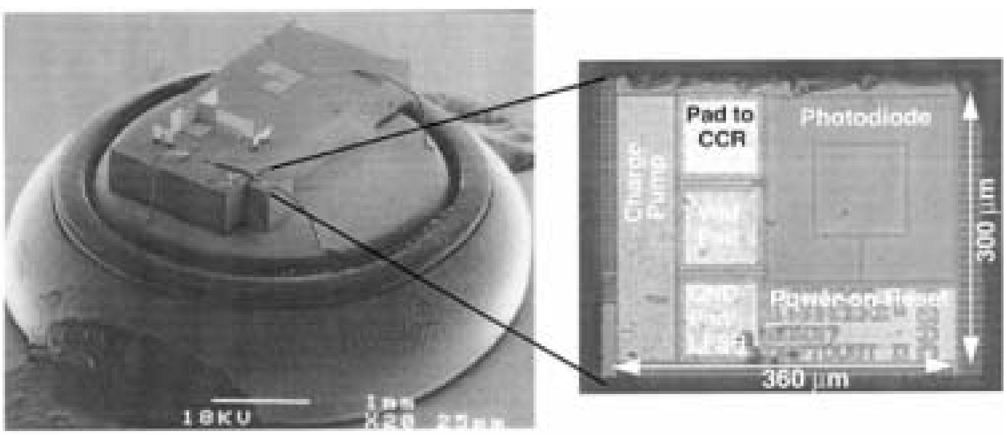

Figure C.23. Photograph of an early version of a "smart dust" system that includes the battery and other chips for sensing temperature and communicating via corner-cube reflectors.

During the past decade much work has been done on the development of interface circuits for sensors, such as for measuring pressure and acceleration. In general, sensors do not provide usable output without some type of signal conditioning. In the case of capacitive, surface micromachined accelerometers, the signal conditioning can include capacitive-to-voltage conversion, amplification, filtering, and calibration to create an analog 0 to 5 V output. Examples of this type of signal conditioning are in production at Motorola, Analog Devices, and Microsensors (Fig. C.24).

(a) (b) (c)

Figure C.24. Examples of capacitive sensor readout chips: a) Motorola's 2-chip accelerometer with a CMOS signal conditioning die that performs C-V conversion, b) Analog Device's integrated accelerometer with integrated biCMOS signal conditioning circuitry, and c) Microsensor's Universal Capacitive Readout chip that can be purchased independently for capacitive sensor signal conditioning.

Similarly, piezoresistive, bulk micromachined pressure sensors also usually require some type of signal conditioning. Figure C.25 shows an example of added complexity to the signal conditioning over time for the Motorola bulk micromachined pressure sensor family.

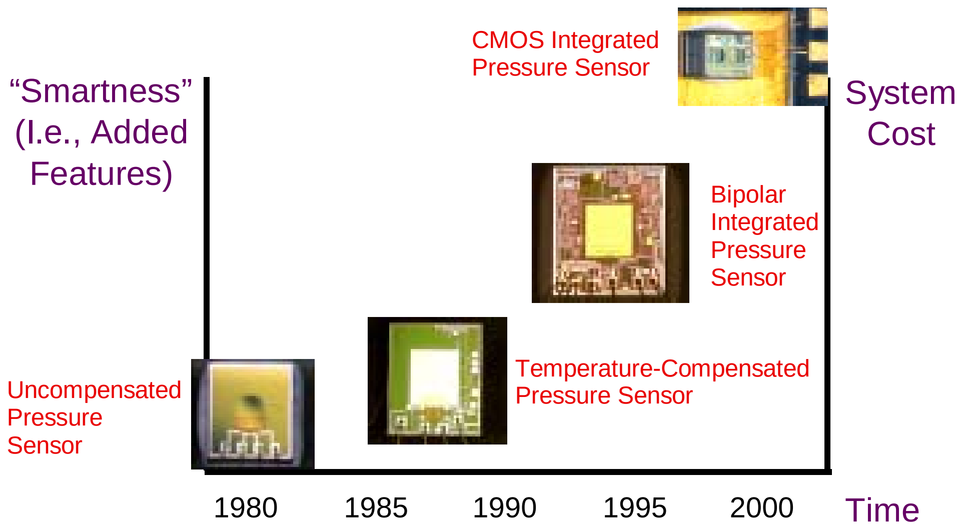

Figure C.25. An example of added complexity to the signal conditioning over time for the Motorola bulk micromachined pressure sensor family.

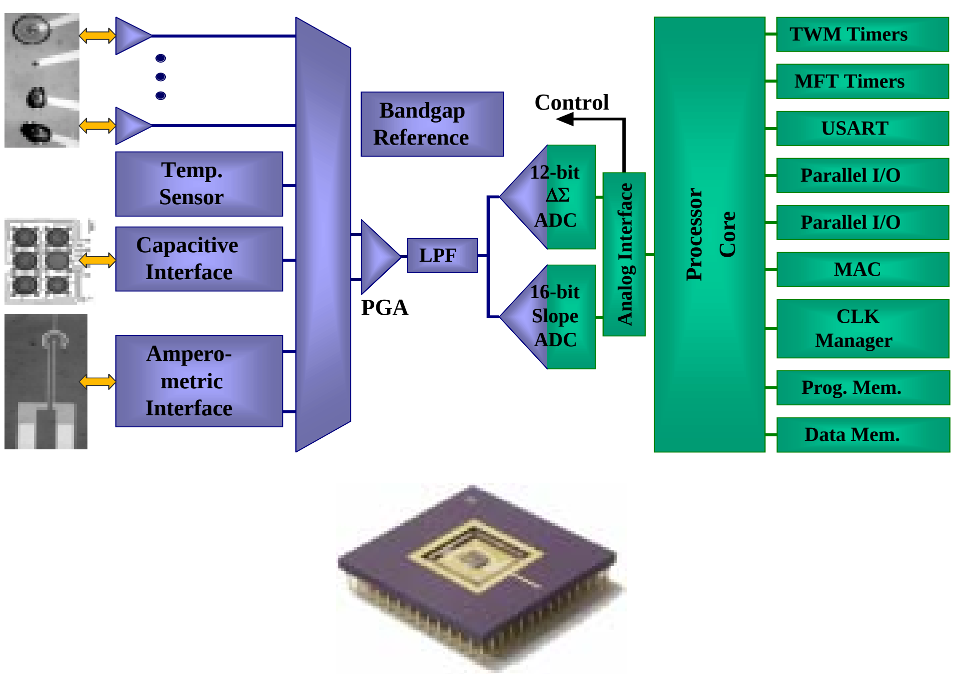

Figure C.26. Block diagram and chip photograph of a transducer's microcontroller chip with sensor readout circuits for a variety of sensors, and on-chip signal processing and control electronics for processing sensor information (Kraver *et al.* 2000).

As microsystems are further developed, chips that include a variety of other analog and signal processing functions are developed. Many of these include standardized interfaces to allow multiple sensors to operate on a single standard bus. Microcontrollers, and in many instances on-chip analog-digital converters, are included on these chips to allow the sensing/actuating system operate in much the same way as standard digital circuits do. These chips can be addressed, provide on-chip references and timers, and provide a variety of signal processing functions to allow them function in a standard digital system. One such system approach is shown in Figure C.26 (Kraver *et al.* 2000). This chip operates from a single 3V supply and includes generic interfaces for capacitive sensors such as pressure and acceleration, chemical sensors, and temperature sensors. The chip is fabricated using a standard foundry CMOS in 0.25µm or smaller features. Using standard CMOS is desirable because it allows the designer to scale feature sizes as new generation of CMOS technology is developed by the IC industry.

Another important requirement in many emerging applications is low-power operation. Standard CMOS offers another feature that can be exploited for MEMS applications, namely its low-power and low-voltage capability. As voltage levels are scaled down in standard VLSI systems, circuit designers for MEMS applications can use the lower supply voltage to incorporate ever increasing levels of signal processing circuitry into sensor readout chips without increasing power dissipation. Supply voltages are now scaled down to 1.5V, and 0.9V circuit technologies are being utilized in the microelectronics industry. One of the important challenges that analog circuit designers face is the need for maintaining high resolution and accuracy in the face of shrinking supply voltage levels. New circuit techniques and improved sensor design have allowed circuit designers of sensor interfaces circumvent some of these problems. Figure C.27 shows the block diagram of a standard sensor interface chip being developed at the University of Michigan (Kraver *et al.* 2000). This chip will operate from a single 1.5V coin cell battery and will include all the functions necessary for reading out a variety of sensor signals. Future generations of this chip are also being designed for operation from a 0.9V supply.

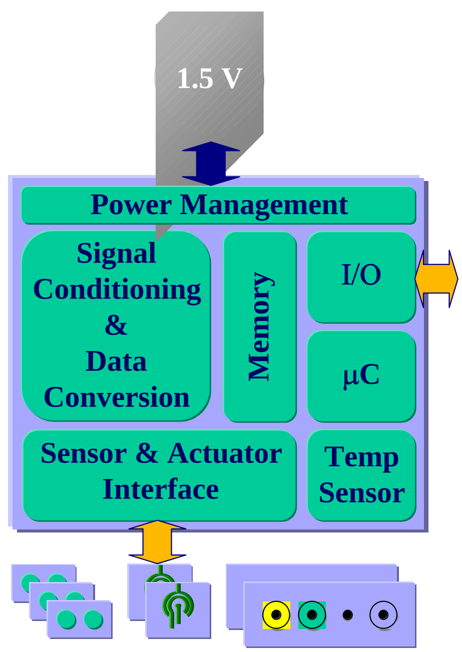

Figure C.27. Block diagram of a low-voltage, low-power MEMS interface chip designed using standard CMOS technology operating from a single 1-1.5V supply provided by a coin cell battery (Kraver *et al.* 2000).

One of the most important applications of circuits in MEMS is in biomedical devices. In particular, implantable biomedical devices require electronics for signal amplification, filtering, and AD conversion, in addition to circuitry for wireless telemetry operation and data communication. One of the most advanced and aggressive approaches to MEMS-circuit integration and microsystem implementation is that demonstrated by a group at the University of Michigan. Implantable recording and stimulating microprobes capable of interfacing with the nervous system are needed to overcome biological disorders such as deafness, blindness, and other nervous system disorders such as epilepsy and Parkinson's disease (Gingrich *et al.* 2001). In these devices, large arrays of recording and stimulating electrodes (containing several hundred individual recording and stimulation sites) are fabricated using silicon micromachining technology. An example of one such implantable microsystem is shown in Figure C.28 where an array of silicon micromachined probes is assembled into a 3-D microsystem. Each probe contains electronics for delivering a programmable current pulse through individual sites for electrical stimulation of individual neurons. The circuitry contains addressing and programming functions as well as an array of 8-bit DA converters that are integrated on individual probe substrates.

Wireless operation is critical and often mandatory for many biomedical devices, especially those that require full implantation. This requires that power and data be communicated with the biomedical device using a wireless link. The most practical approach to wireless data and power transfer is using RF telemetry. This approach has been used by the pacemaker industry for many decades for programming and recharging batteries. The technology has advanced to the point where it is now being used routinely in implantable cochlear prostheses. In the United States, the main player in implantable cochlear prostheses is Advanced Bionics, which is aggressively pursuing the development of next generation implantable prostheses. A version of an implantable cochlear electrode developed by Advanced Bionics is shown in Figure C.29 (www.advancedbionics.com).

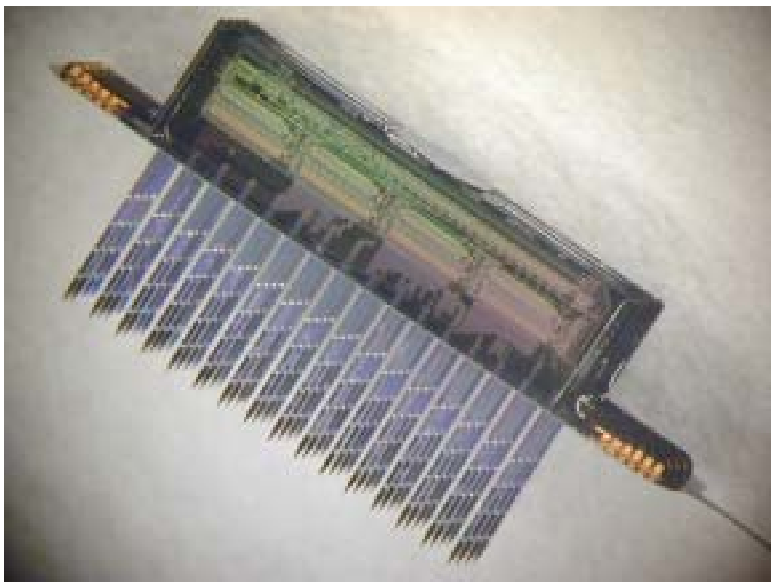

Figure C.28. A 3-D stimulating microprobe array containing 4 different probe substrates assembled onto a support platform. There are a total of 256 stimulating sites on this 3-D probe. Each probe contains electronics for addressing and programming an array of D-A converters and current drivers for delivery of precise current pulses to individual neurons in the brain (Gingrich *et al.* 2001).

Figure C.29. Cochlear implant from Advanced Bionics (www.advancedbionics.com).

Future implantable microsystems will all have to be wireless; and because of their much smaller size, the telemetry systems also have to be miniaturized, made more efficient, and at the same time provide more functionality. The University of Michigan has been actively involved in the design of such next-generation miniature telemetry systems. For next generation cochlear and visual prostheses with silicon probes, a fully implantable telemetry system is being designed as shown in Figure C.30. This system will interface with 3-D probe arrays and will provide power, data, a clock, and program information to individual probes. The telemetry electronics is integrated on another circuit chip that is located on the same platform that supports the probes. Figure C.31 shows the layout of a foundry CMOS circuit chip that implements the functions necessary for full wireless operation of biomedical microsystems. Note that this chip is designed in 1.25µm foundry CMOS and has circuit blocks for voltage regulation, data detection using both amplitude-shift-keying (ASK) and frequency-shift-keying (FSK) modulation schemes, clock recovery, and control and signal processing logic (Ghovanloo and Najafi 2002). It is believed that as MEMS and microsystems are developed further, these wireless chips will become even more important.

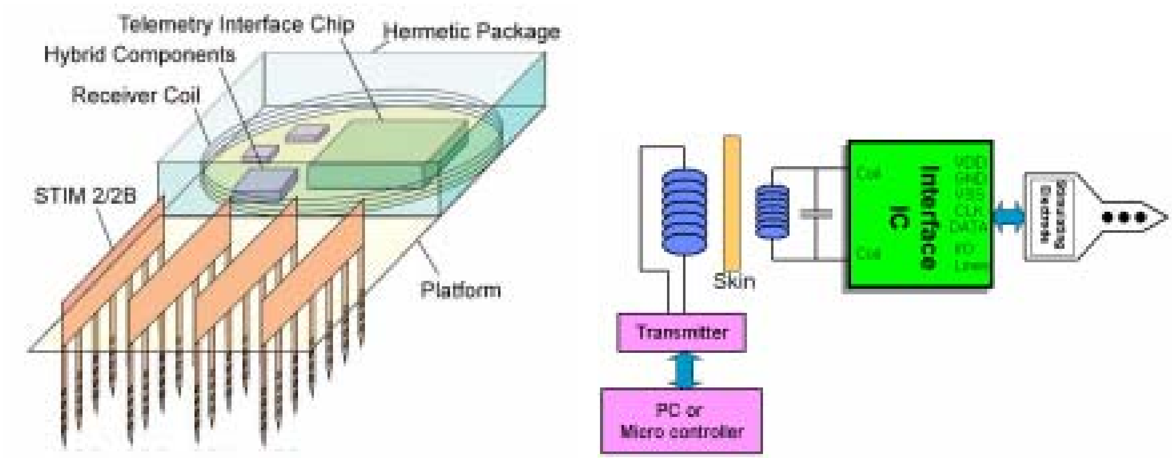

Figure C.30. System architecture and block diagram of next-generation wireless telemetry microsystems (Ghovanloo and Najafi 2002).

Figure C.31. Layout of a CMOS chip designed for implantable biomedical microsystems.

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BACKEND PROCESSES AND TECHNOLOGIES

Packaging, assembly, trimming/calibration, and testing MEMS/MST devices represent a considerable portion of the cost of MEMS/MST products. Swift (1998) and Schuster (1998) both showed that packaging and testing can represent over 50% of the product cost for a microsystem. Discussion during each of the last two "Commercialization of Microsystems" conferences has confirmed this point. In fact, often industrial MEMS engineers and managers suggest that a typical cost breakdown is roughly 33% silicon content, 33% package, and 33% test. It has been reported, in some cases, as greater than 70% packaging cost vs. silicon content (Madou 1997; Allan 1997; Reichl 1991; Song 1997; Eddy and Sparks 1998; Beardmore 1997). Furthermore, of this silicon content, often less than half the cost is due to the microsensor or actuators. The rest of the silicon content is the control or interface electronics cost.

A complete overview of the backend assembly and test technologies can be found in Chapter 7 of P. Rai-Choudhury's *MEMS and MOEMS: Technology and Applications* (2000). The section represents a summary of that review. Packaging MEMS/MST devices poses unique challenges when compared with more conventional electronic packaging because the MEM device can mistake physical signals induced by the package for signals from the environment (Ristic and Shah 1996). This problem was observed very early in the development of sensors and actuators. Senturia and Smith noted, "it is necessary to design the microsensor and the package AT THE SAME TIME" (1988). They made two very important observations in this work: 'Packaging people' and 'sensor people' are usually not the same people, and they do not always work well together; and consideration of the package can help eliminate possible sensor designs because they would not be feasible in a particular package.

The package can play a vital functional role in the productization of a microsystem. For example, the package can isolate the induced stress from the mounting of the device (Eddy and Sparks 1998; Bicking *et al.* 1985); it can make the electronics compatible with the harsh environment (Eddy and Sparks 1998; Ristic and M. Shah 1996); and it can even be an integral part of the microsystem (e.g., mechatronics packaging). While MEMS engineers often discuss integration as a technique for placing transducers and electronics on the same IC chip, integration can also refer to the combination of typical package functions onto the silicon (Ristic and M. Shah 1996; Wise 1991). Wafer bonding is an example of this. In pressure sensors, an absolute vacuum reference can be integrated into the silicon device. Furthermore, many microsystems will not be integrated monolithically; therefore, multichip packaging will be required (Wise 1991).

Finally, efforts of packaging and testing for MEMS have been significantly under-represented in academic and trade publications. Considering the cost breakdown, little has been written on the assembly and test for MEMS. Much of the grant money, academic research, and publications are on the micromachined transducer itself and not the rest of the microsystem. Recently, that point has been highlighted in several conferences (Solid-State Sensors and Actuators 1998; Commercialization of Microsystems 1996 and 1998). Publications that have summarized the slow breakthrough of microsystems into commercial application have pointed to the following limitations of the technology (Allan 1997; Commercialization of Microsystems 1996 and 1998; Detlefs 1998):

- CAD
- Standards
- Assembly techniques (Wise 1991)
- Process tools (both front-end and back-end tools)
- Test equipment, processes and standards
- Harsh media compatibility (Madou 1997; Ristic and Shah 1996; Detlefs 1998)
- Reliability standards and results
- Packaging techniques and processes

To create MEMS packages, the following common processes are used: bonding, wafer sawing/scribing, pick and place, die attach, wirebonding/interconnection, encapsulation, overmolding, trimming, and final testing. Figure C.32 shows a typical flow diagram for assembly. Specifically, this is an example of a pressure sensor assembly and test flow.

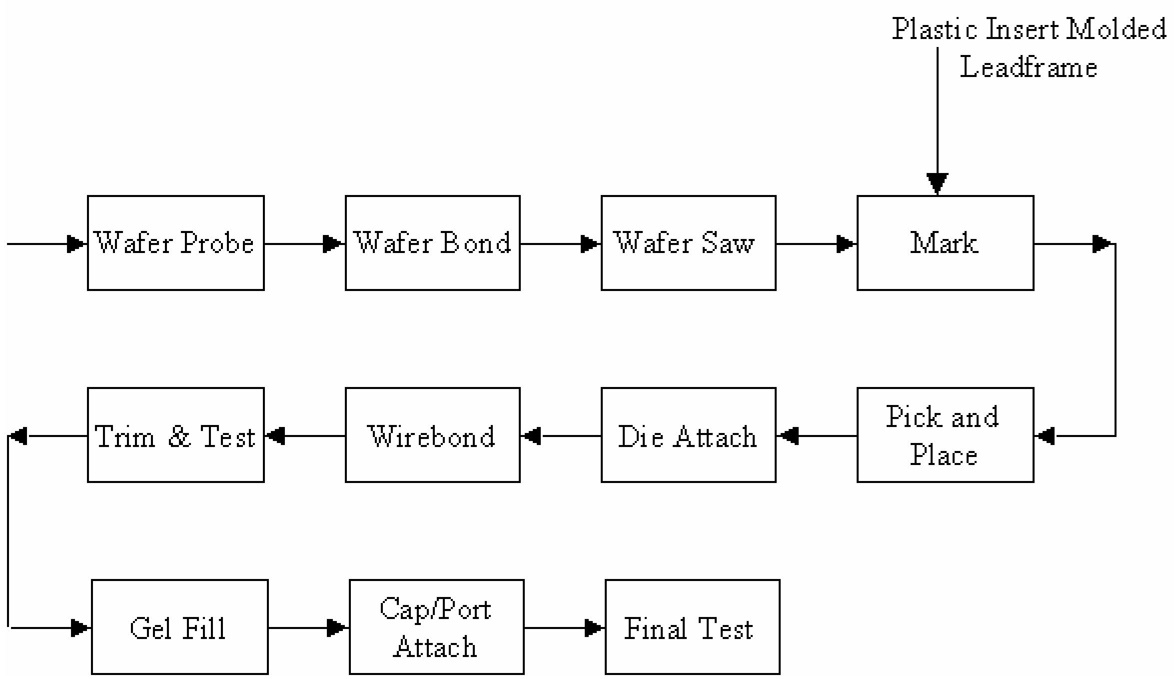


Figure C.32. An example flow diagram for a typical pressure sensor assembly process flow.

In the case of absolute pressure sensors, wafer-level packaging is used (Fig. C.33) to create an absolute vacuum reference. Similarly, some accelerometers or micromachined resonators also require wafer-level bonding to create a controlled atmosphere for the device (Fig. C.34). Complete reviews of wafer-to-wafer bonding for MEMS are given by Schmidt (1998) and Ko *et al.* (1985).

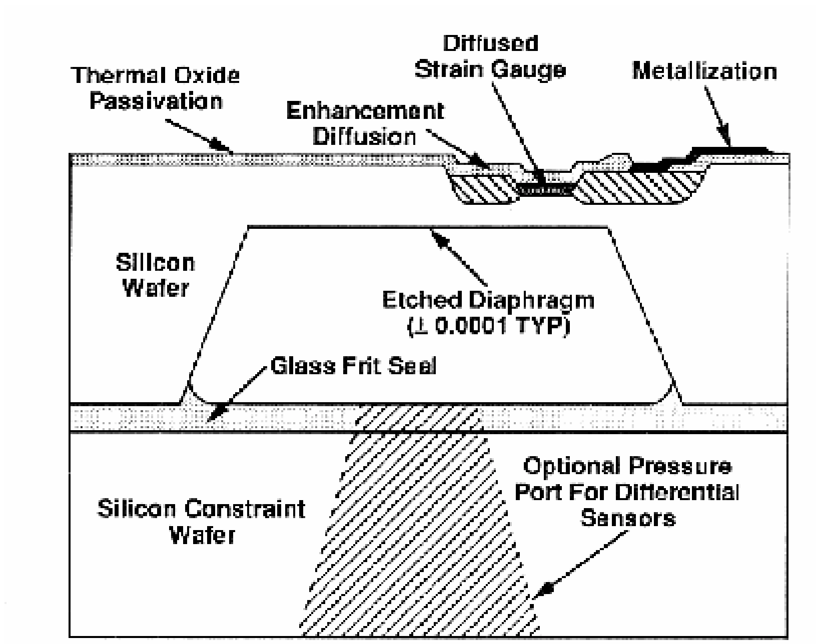


Figure C.33. Wafer bonding to create an absolute vacuum cavity for an absolute pressure sensor device (Ristic 1994).

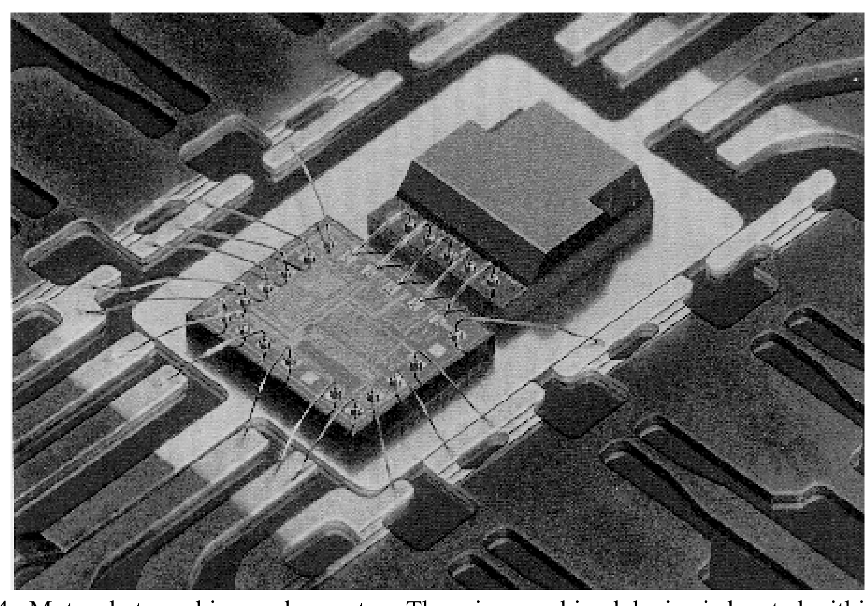


Figure C.34. Motorola two-chip accelerometer. The micromachined device is located within the wafer-bonded die (right side). Wafer bonding is done using an adhesive glass frit for the hermetic wafer-level sealing of an accelerometer device prior to wafer saw and assembly (Ristic 1994).

Besides protecting the device in operation, the wafer-bonded accelerometer in Figure C.34 is also protected during the assembly process, including during wafer sawing (Ristic and Shah 1996; Kniffin and Shah 1996). However, in the case of the Analog Devices production accelerometer, wafer-level packaging is not employed, so a special upside-down sawing process is used (Figure C.35).

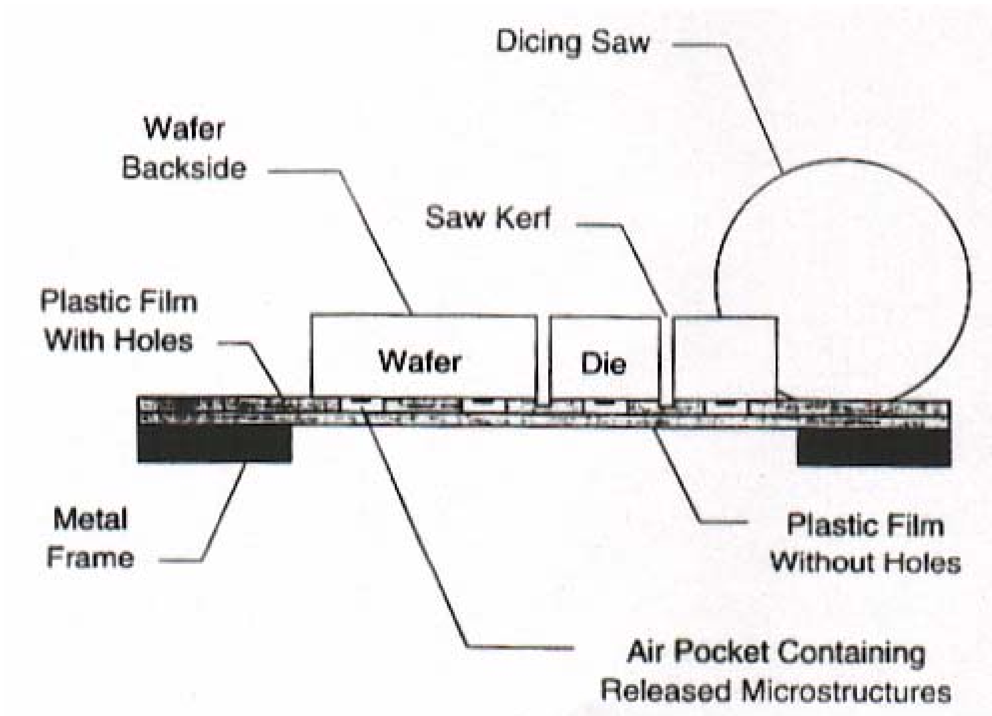


Figure C.35. Upside-down wafer sawing process used to protect the Analog Devices accelerometer during die separation (Chau and Sulouff 1998).

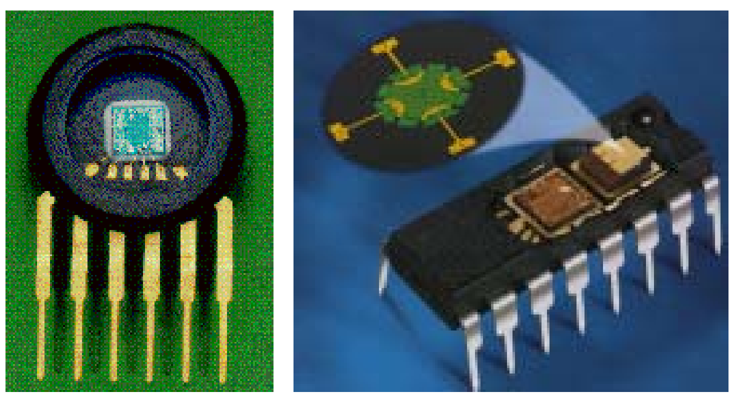
Following this die separation, a modified pick and place tool is used to minimize the disturbance of the surface micromachined structure during the operation (Chau and Sulouff 1998). Some research has been performed over the past several years in the United States to investigate the possibility of self-assembly. Yeh *et al.* have observed trapping of semiconductor ICs in micromachined wells (1994). Cohn *et al.* have modified this technique by adding electrostatic alignment of the die prior to settling into the cavities (1995). After the die is bonded onto the substrate, wirebonding and final encapsulation, sealing, or overmolding is performed. Figure C.36 shows some MEMS packages.

In high volume manufacturing, a distribution of electrical parameters from device to device is observed. The method for minimizing the effect of that variation on yield loss is called trimming. Manual calibration, laser trimming, zener zap, electronic calibration (Summers *et al.* 1996), polysilicon resistor trimming (Feldbaumer *et al.* 1995; Ryan and Bryzek 1995), E/EPROM, and other methods are used for this purpose. In the case of a Motorola bipolar pressure sensor or an Analog Devices accelerometer, the device is laser trimmed.

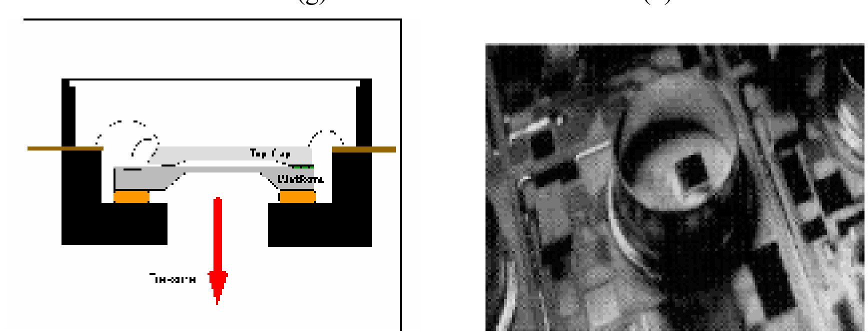
(a) (b)

(c) (d)

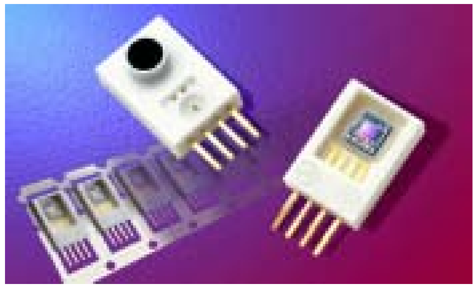
(e) (f)



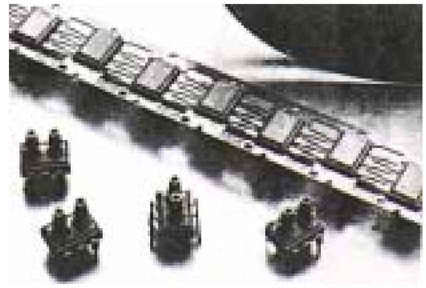
(g) (h)



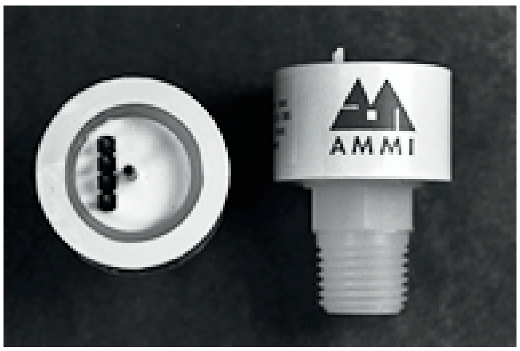
(i) (j)



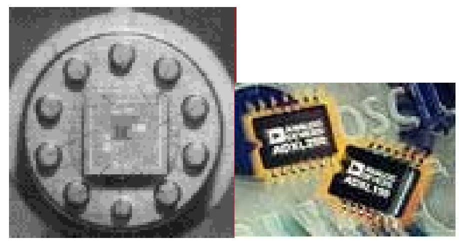
(k)



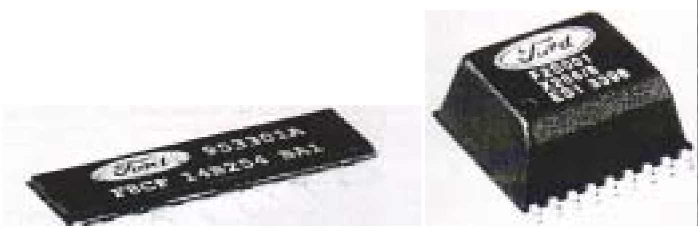
(l)



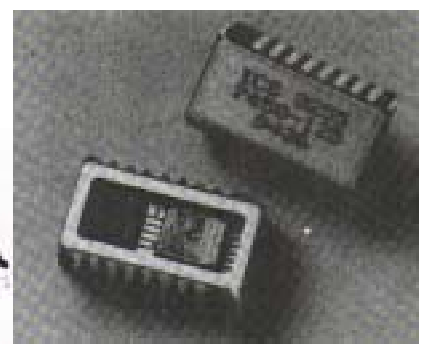
(m)



(n)



(o)



(p)

Figure C.36. Examples of MEMS packages, including a) pressure sensors mounted to TO-Header packages [http://www.novasensor.com/, ca. 1/31/99]; b) a variety of pressure sensors mounted in ceramic packages in various styles [http: //www.novasensor.com/, ca. 1/31/99]; c) media compatible pressure sensors using stainless steel diaphragm and silicone oil filled-packages [http: //www.novasensor.com/, ca. 1/31/99] (Ryan and Bryzek 1995); d) a high pressure metal package for housing pressure sensors [http://www.mot.com/AECS/General/AIEGSensors/index.html, ca. 2/99]; e) The Motorola unibody package using polyester thermoplastic housing material (Ristic 1994; Adams 1987); f) the Motorola manifold absolute pressure (MAP) module [http://www.mot.com/AECS/General/AIEGSensors/index.html, ca. 2/99]; g) an example of the transfer-molded, thermoset (i.e., epoxy) unibody pressure sensor package by Motorola; h) an overmolded epoxy package for the Motorola accelerometer; i) glass frit bonding used to create a backside absolute pressure sensor for media compatibility (Sooriakumar *et al.* ; Sooriakumar *et al.* 1995; Goldman *et al.* 1997; Goldman *et al.* 1998); j) an automotive pressure sensor on a ceramic substrate with a metal can that isolates the pressure sensor, and harsh media, from the rest of the circuit and pressure sensor module (Ristic 1994); k) a polysulfone thermoplastic disposable medical pressure sensor package from Motorola; l) an example of a single-stranded, interdigitated leadframe array (Mallon *et al.* 1988); m) a secondary diaphragm package produced by AMMI to create a media compatible pressure sensor package; n) accelerometer packages from ADI—a header-style package and a SOIC-style package (Chau and Sulouff 1998; Core *et al.* 1993) [http://www.analog.com/industry/iMEMS/, ca. May, 1999]; o) the Motorola accelerometer in a plastic package and the Ford Microelectronics accelerometer in a plastic package (Stalnaker *et al.* 1997); and p) the EG&G IC Sensor accelerometer package.

An attempt at multichip packaging of MEMS and electronics using flip-chip technology is the SMARTMUMPs process available from MCNC. In this process a standardized electronics die is flip-chip attached onto a MUMPs MEMS die as shown in Figure C.37 (Koester *et al.* 1996). The MUMPs die is released prior to attachment of the electronics die. A drawback of this integration technique is that the electronics die blocks physical access to the MEMS devices located underneath it.

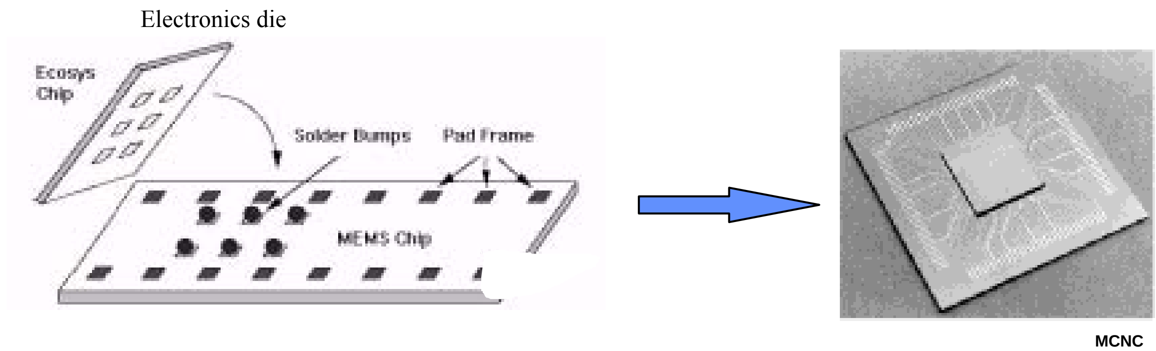


Figure C.37. SMARTMUMPs flip chip attachment from MCNC (Koester *et al.* 1996).

An example of direct metal deposition is the General Electric's High Density Interconnect (HDI) process. This process uses the 'die first' or patterned overlay concept (refer to Figure C.38). In the HDI process, holes are milled in the substrate to house the various die. After the die are placed and bonded in the substrate, Kapton sheets are glued over the top; and via holes are created through a laser drilling process. Metal is then deposited and patterned to form interconnects. The Kapton lamination and metallization process is repeated until all the interconnect layers are created (Daum *et al.* 1993).

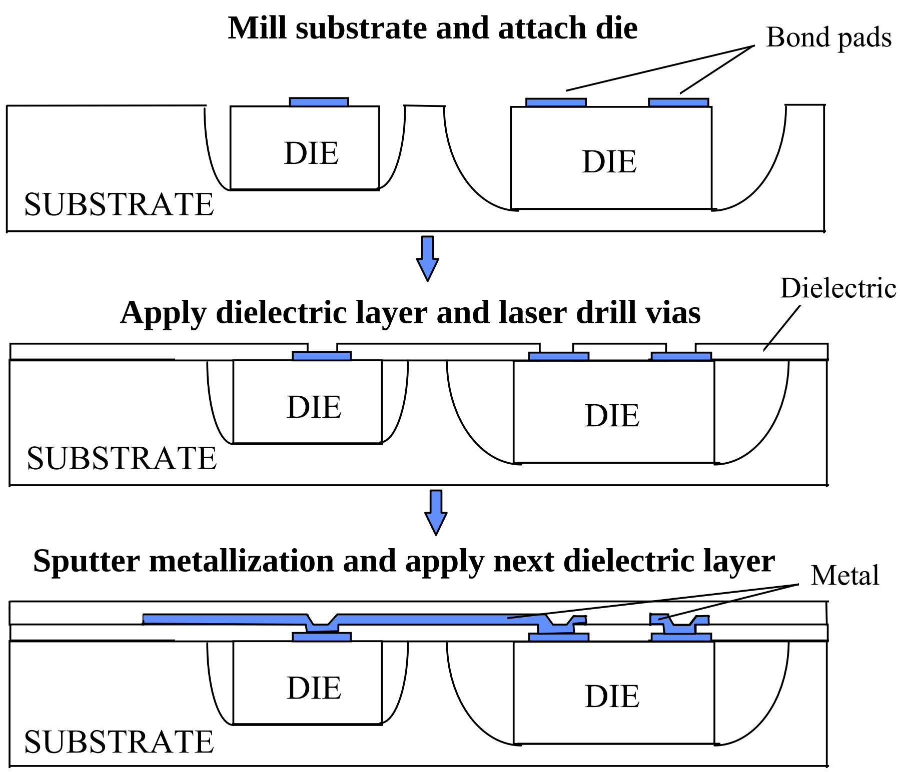


Figure C.38. The HDI process (Daum *et al.* 1993; Butler 1998).

Optical MEMS packaging creates additional challenges. The interface to a system involves electrical and optical connections. Electrical signals that are supplied through the package to the DMD are thus converted to mechanical movement of the DMD pixels. Optical illumination, which is also coupled into the package, reflects off the surface of the DMD pixels and into a projection system. The movement of these reflective DMD pixels allows for the spatial modulation of light: light is steered into or out of a projection lens system. An example of optical coupling is depicted in Figure C.39.

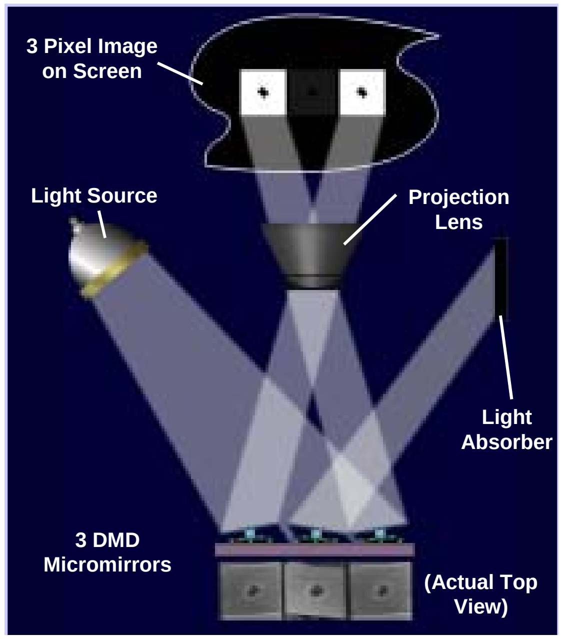
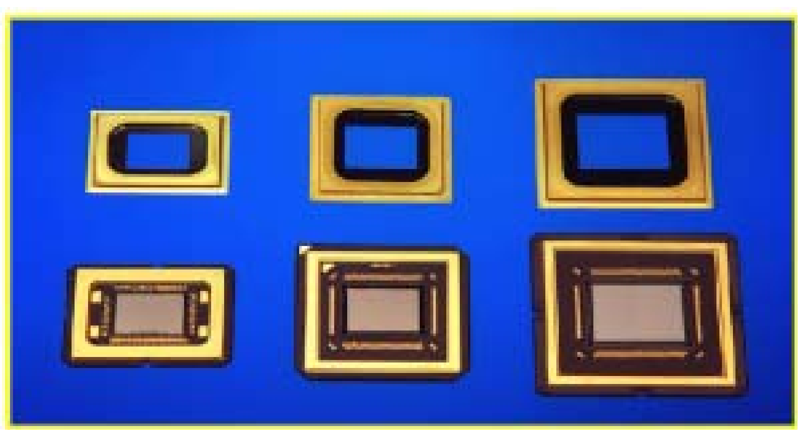


Figure C.39. Optical schematic of projection operation.

The DMD package is thus an application specific design: the entire design was developed internally. Requirements for the optical lid include minimal light losses, optical flatness/parallelism, an optical aperture, and the capability to withstand a parallel resistance seam welding process that induces mechanical and thermal stresses.

The substrate that the DMD device is mounted on is a land grid array (LGA) ceramic header product. An aluminum heat sink is mounted on the backside of the ceramic header for thermal heat dissipation. The window assembly has a large non-round matched glass-to-metal seal and is post-processed by polishing and coating the window. The window and substrate for three types of DMD packages are shown in Figure C.40.



(a) (b) (c)

Figure C.40. DMD Windows and Substrates: (a) .7" SVGA resolution, (b) .9" XGA resolution, (c) 1.1" SXGA resolution

The lid assembly consists of two-piece parts, a stamped kovar frame and Corning 7056 glass. Packaging material selection, especially matching coefficients of thermal expansion (CTE), is important for a mechanical and environmental robust package. Since the CTE of the metal and glass are very close, a matched glass-to-metal seal is made by means of a belt furnace with a peak temperature of approximately 1000°C. After the glass-to-metal fuse is complete, the glass of the window assembly is processed through a double-sided grinding and polishing operation. The kovar frame is then plated with 2-8 µm of nickel and a minimum of 1-2 µm of gold. It is important that the surface quality of the glass not be damaged when the polished window assembly is exposed to the chemical baths during the plating process.

Two coatings are then applied to the window assembly. First, a low reflectance coating is applied on the surface of the glass that will be on the inside of the package after the window-attach process. A photomask is applied, and this low reflectance coating is removed or etched away to form a clear window aperture. To achieve a sharp aperture edge definition (i.e., less than 20 µm protrusions), the etch chemistry and process time used during the process are critical. The purpose of the window aperture is to hide features outside of the DMD active array. Features such as bond wires are blocked from the illumination source. After the aperture coating is etched, the photomask is removed and MgF_2 antireflective (AR) coatings are applied to both sides of the glass. The required average transmittance of the AR coatings is greater than 98%, and the reflectance is less than 0.5%. Finally, two getter strips are adhesively attached to the internal region of the window assembly. The purpose of the getter is to control contaminants (specifically moisture). Stiction mitigation is the primary driver for the inclusion of the getter strips: Moisture (i.e., capillary attraction) can cause the pixel to stick upon landing. The complete package is shown in Figure C.41.

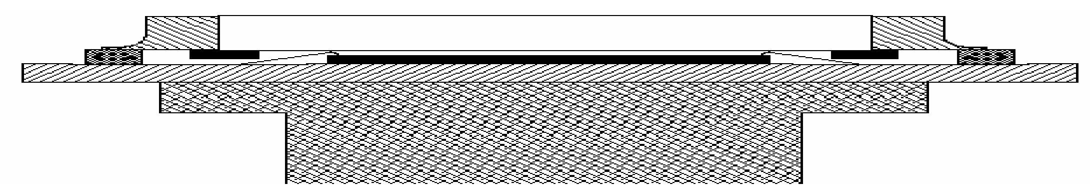


Figure C.41. Side view of DMD hermetic package.

Finally, MCNC/Cronos has recently introduced a microrelay product (Figure C.42). Initial shipments are based on ceramic packages, while an injection molded plastic version is planned for future production (Paultre 1999). The package is PCM-CIA compliant and contains from two to eight switches per package. Each switch is electrically tested to insure that it conforms to specifications. Reliability tests have shown that these devices perform within specifications at over a million cycles. Their robust relay design lends itself well to conventional packaging technology and does not place unusual requirements on the packaging.

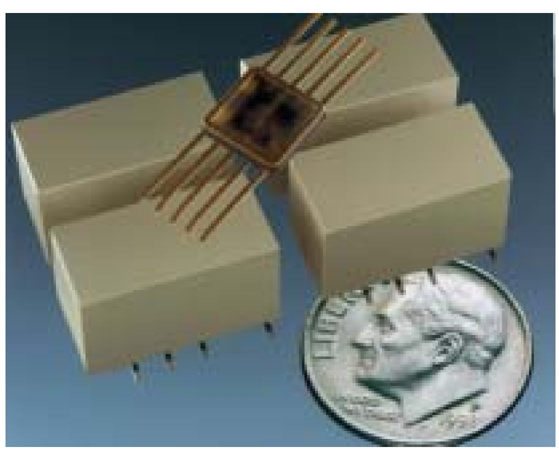


Figure C.42. Cronos Integrated Microsystems (formerly MCNC MEMS Technology Center) microrelay product.

In general, packaging of MEMS and optical MEMS devices is an outgrowth of the IC packaging industry and the hybrid packaging industry (Ristic and Shah 1996; Tummala and Rymaszewski 1989). Packages for MEMS and optical MEMS devices typically have the following requirements (Madou 1997; Ristic and Shah 1996; Ko 1994; Morrissey *et al.* 1998; Romig *et al.* 1997; Bossche *et al.* 1998):

- Interaction with the environment (e.g., media compatibility or hermetic vacuum sealing to protect accelerometers, resonators, etc.)
- Low cost
- Small size
- High reliability and quality
- Standardization (although custom packaging for MEMS and optical MEMS is more the rule than the exception)
- Acceptable electrical interconnection (e.g., minimum power supply voltage drop, self-inductance, cross-talk, capacitive loading, adequate signal redistribution, and perhaps electrical feedthroughs)
- Thermal management (i.e., power dissipation and matching CTEs with substrates to minimize package-induced stress)
- Acceptable mechanical interconnection (e.g., porting for pressure or flow sensors and mounting techniques that do not apply undue stress to the device yet support the device appropriately)
- Protection from electromagnetic interference
- Testability and trimmability (e.g., internal test/trim nodes)
- Precision alignment (especially for optical MEMS)
- Accommodation for optical interconnection either with optical fiber or free-space
- Mechanical protection and stress isolation

The uniqueness of some of these requirements, the large amount of intellectual property in the packaging and testing of MEMS/MST devices, and the high portion of the product cost make these backend processes a source of significant industrial development activities and a source of significant industrial secrecy.

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COMMERCIALIZATION OF MICROSYSTEMS TECHNOLOGIES

There have been several overviews of the MEMS/MST market in the United States. Among the most recent are from the Commercialization of Microsystems 2000 conference in Santa Fe, NM and in the article by Bryzek (2001). Figure C.43 illustrates a recent estimate of the MEMS/MOEMS market worldwide. This chart will be used to organize the following section.

Product	**2000 Sales**	**2005 Sales**	**Growth**
MOEMS	\$100M	\$5,000M	281%/y
Fluidics/Biotech	\$10M	\$300M	43%/y
Displays	\$200M	\$1,000M	38%/y
RF & ICs	\$50M	\$250M	38%/y
Data storage	\$50M	\$250M	38%/y
Other	\$50M	\$150M	25%/y
Pressure sensors	\$1,600M	\$2,500M	10%/y
Inertial sensors	\$400M	\$800M	7%/y
Total	**\$2,500M**	**\$10,250M**	**33%/y**

Figure C.43. The MEMS/MST market worldwide, as estimated by J. Bryzek (2001).

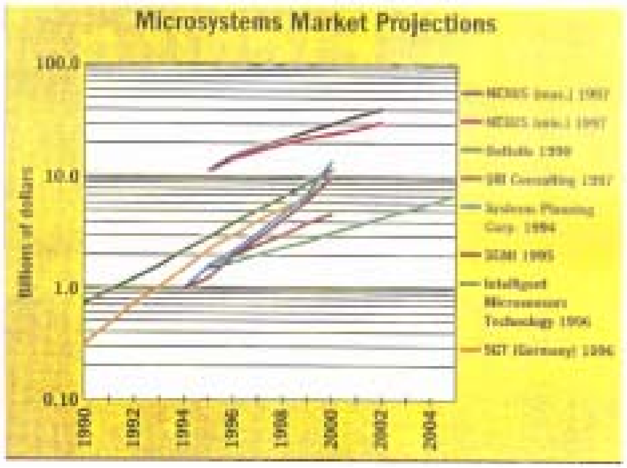

Figure C.44. Estimates of the MST market worldwide, summarized from several sources (Detlefs 1998).

This estimate is not dissimilar to several others that have been summarized in Figure C.44. However, Delphi Corp. estimates that the sensor and actuator market is a $27 billion industry. More than $13 billion is generated in the automotive industry, and this area is anticipated to grow to $21 billion by 2010 (http://www.delphiauto.com/news/pressReleases/pr1689-06042001).

Each of these estimates represent the microsystem market: that is, the overall system and not simply the MEMS component. Some inputs suggest that the MEMS component industry supporting this microsystem market is on the order of $1B. One thing that has become evident is that the MEMS market encompasses several dissimilar technologies and, therefore, is somewhat fragmented.

Supply Chain for Microsystem Market in United States

The MEMS industry in the United States can be analyzed by looking at each part of the microsystem supply chain: MEMS-specific tool suppliers, foundries, design/development organizations, full MEMS production firms, and MEMS product users (MST producers). Additional infrastructure, including industrial groups, conferences, and other locations of information on the MEMS industry are also provided.

MEMS-Specific Tool Suppliers

Some companies have begun producing tools that are specifically targeted for the MEMS industry. Table C.2 lists examples of U.S. firms that are doing this.

Table C.2
U.S. Firms Providing MEMS-Specific Tools

Firm	Tools Produced	URL
Ultratech Stepper	1X and reduction lithography systems with the resolution, depth of focus, alignment and substrate handling performance designed for MEMS	http://www.ultratech.com
Electronic Visions	Precision wafer bonding, including separation of alignment from the bonding procedure, a unique bond tool design, and the universal bond chamber designs	http://www.evgroup.com
Surface Technology Systems (STS)	Although headquartered in Wales, STS has significant presence in Silicon Valley, where they provide a dedicated cassette-to-cassette cluster platform for MEMS deep silicon etch configured with either a standard or high rate ASE® source; also, commercially-available XeF_2 etchers	http://www.stsystems.com
SC Fluids	Manufactures an automatically operating Supercritical CO_2 Cleaner/Dryer to release surface MEMS structures. Stiction problems are avoided by using this machine. It handles wafers up to a diameter of 6”	http://www.scfluids.com
Intellisense	IntelliSuite, the first commercial CAD for MEMS™ tool, is the solution for the design, simulation and optimization of MEMS	http://www.intellisense.com
Coventor	Offers a fully integrated suite of products and services that includes • Development software • Engineering and consulting services • A growing portfolio of diverse intellectual property • Manufacturing support • Pioneering expertise in cutting edge technologies such as MEMS • Market expertise in optical communications, RF wireless communications, biotechnology, and other markets such as inertial sensors and microfluidics	http://www.coventor.com/
Tanner Research Inc.	MEMS Pro – Integrated tool suite that includes a full custom layout editor, cross section viewer, layout synthesis, design verification, libraries and setups suitable for both MEMS and IC design needs	http://www.tanner.com
Virginia Semiconductor	Silicon substract manufacturer—some products specific for MEMS	http://www.virginiasemi.com
FSI International	YieldUP® 4000 offers temperature-controlled, recirculated dilute HF chemistry. The system has an etching tank and a rinse/dry tank featuring Surface Tension Gradient (STG™) technology. It can be used on a variety of substrates, including wafers, disks, and flat panels.	http://www.fsi-intl.com/products/scdclean.html
Exponent	Exponent provides design, characterization, testing, and development assistance to both the MEMS industry and firms implementing MEMS technology.	http://www.fail.com/practices/MEMS/index.html

Foundries

Within the United States, there are several foundries that specialize in manufacturing MEMS-based products. Table C.3 lists examples of U.S. foundries in MEMS.

Table C.3
U.S. Foundries in MEMS

Foundry	MEMS-Based Products	URL
Sony USA		
Advanced MicroMachines Incorporated		http://www.memslink.com/
Integrated Sensing Solutions	ISSYS exists to develop and produce the best pressure and flow sensors and sensing systems in the world. Our products provide the highest accuracy, can fit the smallest sizes, and have unmatched corrosion resistance.	http://www.mems-issys.com/
Intellisense	A leader in MEMS development and high-end volume manufacturing, IntelliSense offers a uniquely broad array of processes in a flexible 50,000 square foot facility.	http://www.intellisense.com/
Advanced Custom Sensors, Inc.	MEMS packaging and product commercialization	http://www.acsensor.com
Cronos Microsystems Inc.	Cronos was acquired by JDS Uniphase in April 2000. Cronos is the only MEMS supplier that provides bulk, surface, and high-aspect ratio (LIGA) micromachining—the three key processes used to fabricate MEMS devices.	http://www.memsrus.com/

Companies Designing and Producing MEMS Products

Table C.4 shows a list of companies that specialize in MEMS-based product development, and Table C.5 shows a list of companies that are designing and producing MEMS products in the United States.

Table C.4
U.S. MEMS-Based Design-Specific Organizations

Organization	MEMS-Based Product Development	URL
Advanced MicroMachines Incorporated		http://www.memslink.com/
EG&G IC Sensors	Bulk Micromachined Piezoresistive Pressure Sensor process 2. Bulk Micromachined Piezoresistive Accelerometer process 3. Bulk Micromachined Capacitive Accelerometer process 4. Fully custom bulk or surface micromachined process 5. Full die assembly, packaging, and testing facilities	http://mems.isi.edu/mems/yp/mems_centers/IC_Sensors.html
Intellisense	A leader in MEMS development and high-end volume manufacturing, IntelliSense offers a uniquely broad array of processes in a flexible 50,000 square foot facility.	http://www.intellisense.com/
MicroAssembly	MicroAssembly Technologies was founded in 1998 to provide MEMS integration and packaging solutions for challenging fiber optic and wireless applications.	http://www.microassembly.com/

Table C.5
U.S. MEMS Design and Production Houses

Field of MEMS application		
Company	**Application/Product**	**URL**
	Optical MEMS	
Intellisense/Corning	Optical MEMS cross-connects; Corning and Intellisense announced cooperative development agreement in January 2001	http://www.corning.com/inside_corning/news__media/press_releases/2000/000302_intellisense.asp http://www.intellisense.com/
Lucent		
Onix Microsystems	Onix Microsystems was formed to commercialize a key patented technology for Optical switching Engines™ using MEMS-based technologies.	http://www.onixmicrosystems.com/
Optical Micromachines	manufacturer of MEMS based all-**optical** switching subsystems.	http://www.omminc.com/home.html
	Fluidics/Biotech	
Aclara Biosciences	Solution assay minitiarization	http://www.aclara.com/
Cepheid	Cepheid is dedicated to applying breakthrough microfluidics and microelectronics technologies to revolutionary test systems for DNA analysis applications	http://www.cepheid.com/
Orchid Biosystems		http://www.orchidbio.com/
Redwood Microsystems	Redwood Microsystems designs and manufactures silicon microfabricated valves and valve-based subsystems using semiconductor- manufacturing techniques.	http://www.redwoodmicro.com
	Displays	
Silicon Light Machines	Silicon Light Machines was formed to commercialize a broad range of products based on the patented Grating Light Valve™ (GLV™) technology.	http://www.siliconlight.com/
Texas Instruments	Digital Micromirror Display	http://www.dlp.com/dlp/resources/tech_dmd.asp
	RF & ICs	
Discera	Discera replaces the passive (and some active) components on a wireless circuit board with a single micromechanical system that offers exceptional reception quality.	http://www.discera.com/
	Data Storage	
IBM		
Nanochip	Nanochip Inc. is the leader in the design of Micro-Electro-Mechanical Systems (“MEMS”) silicon memory.	http://www.nanochip.com/

Table C.5
U.S. MEMS Design and Production Houses (continued)

Field of MEMS application		
Company	**Application/Product**	**URL**
	Pressure Sensors	
EG&G IC Sensors	Bulk Micromachined Piezoresistive Pressure Sensor process 2. Bulk Micromachined Piezoresistive Accelerometer process 3. Bulk Micromachined Capacitive Accelerometer process 4. Fully custom bulk or surface micromachined process 5. Full die assembly, packaging, and testing facilities	http://mems.isi.edu/mems/yp/mems_centers/IC_Sensors.html
Endevco		
Honeywell MicroSwitch Division		
Kavlico	Kavlico manufactures pressure transducers and sensors utilizing MEMS technology.	http://www.kavlico.com/
Sentir	A division of Merit Medical. **Sentir Semiconductor** manufactures state-of-the-art silicon micromachined sensors for OEM measurement and control applications. These sensors include piezoresistive pressure sensor integrated circuits, custom micromachined microstructures, and ceramic hybrid pressure sensor assemblies.	http://www.sentir.net/
Setra Systems	Pressure transducers	http://www.setra.com/
TRW Novasensor	TRW purchased Lucas in 2000. NovaSensor offers a: 1. Bulk Micromachined Piezoresistive Pressure Sensor process 2. Bulk Micromachined Piezoresistive Accelerometer process 3. Custom and other proprietary bulk or surface micromachined process 4. Automated assembly, packaging, and testing facilities.	http://www.novasensor.com/
	Inertial Sensors	
Analog Devices	Production of integrated surface micromachined accelerometers and angular rate sensors	http://www.analog.com/imems/
Integrated Micro Instruments	Gyroscope design house; acquired by Analog Devices in December 2000	http://www.imi-mems.com/
Kionix	Design and fabrication of angular rate sensors using the SCREAM process	
MEMSIC	MEMSIC is a MEMS IC company offering advanced technologies that can monolithically integrate micro-electro-mechanical structures with standard CMOS mixed signal circuitry on a single silicon chip.	http://www.memsic.com/
Microsensors/ Irvine Sensors	Highly sensitive angular rate gyroscope Surface micromachined silicon The gyro is based on Coriolis tuning fork principle Readout ASIC: low power, ultra-low noise, wide dynamic range De-coupled capacitive pick-off Low cost plastic package	http://www.microsensors.com
Motorola	Production of surface micromachined accelerometers, including CMOS interface ICs	http://e-www.motorola.com/automotive/architectures/sensors.html
BEI Sensors and Systems Co.	Production of quartz tuning fork, angular rate sensors	

Table C.5
U.S. MEMS Design and Production Houses (continued)

Field of MEMS application		
Company	**Application/Product**	**URL**
Other		
Intel	Intel disclosed on 4/25/01 that it is engaged in R&D and investment activities in microelectromechanical systems (MEMS). MEMS is a technology similar to silicon technology.	http://www.intel.com/research/silicon/mems.htm
Fidelica	Fidelica is a leading pioneer of fingerprint authentication in the Biometrics Industry.	http://www.fidelica.com

Companies Using MEMS Products in MST Modules

Delphi Automotive—http://www.delphiauto.com/—By consolidating components, software and wiring into a single, multi- functional device, INTELLEK smart sensors and actuators provide a variety of benefits.

Industry Groups, Organizations, and Conferences

Table C.6
MEMS-related Groups, Organizations, and Conferences

Organization/Event	Description	URL
MEMS Industry Group	The MEMS Industry Group will be the trade association representing the MEMS industry. The mission of MEMS-IG is to provide leadership for U.S. MEMS manufacturers and integrators by being a resource on the critical issues of MEMS technology evolution, global markets, and the state of the industry.	http://www.memsindustrygroup.org/
Transducer Research Foundation	The Transducer Research Foundation (TRF) is a nonprofit organization whose purpose is to stimulate research within the United States in science and engineering, with emphasis on technologies related to transducers and microsystems, and to foster the exchange of ideas and information. A prime activity of the TRF is sponsorship of a biennial workshop on solid-state sensors and actuators that has become popularly known as the "Hilton Head Workshop" because it has been held in Hilton Head, S.C. since its inception in 1984. Technical Digests for recent Hilton Head workshops are available from the TRF office at the location listed below.	http://www-bsac.eecs.berkeley.edu/trf/
MEMS Clearinghouse		http://mems.isi.edu/

Table C.6
MEMS-related Groups, Organizations, and Conferences (continued)

Organization/Event	Description	URL
Roger Grace Associates	Roger Grace Associates is a technology marketing company specializing in MEMS/MST. We provide the following services to companies on a worldwide basis: • Market Research • New Product Definition & Assessment • Business Plan Development • Strategic Marketing • Company Positioning • Sales Network Development • Integrated Marketing Communications; Public Relations; Advertising • Merger & Acquisition Support	
Sandia National Labs		http://mems.sandia.gov/scripts/index.asp
DARPA		
NSF		

MEMS Investment Climate

Table C.7
Select 2001 private equity activity involving MEMS Companies in the United States

Company	Field of interest	Company	Field of interest
HandyLab	Biological	Advanced Integrated Photonics	Optical
Lumicyte	Biological	Agility	Optical
Microlab	Biological	AXSUN	Optical
Micronics	Biological	C Speed	Optical
Molecular Reflections	Biological	Calient	Optical
Mycometrix	Biological	InLight Communications	Optical
Nanostream	Biological	Integrated Micromachines	Optical
Verimetra	Biological	Iolon	Optical
Ion Optics	Chemical sensors	LightConnect	Optical
MEMSIC	Inertial Sensor	MEMS Optical	Optical
Advanced MicroSensors	Infrastructure	Ondax	Optical
Colibrys	Infrastructure	Onix	Optical
Coventor (fka Microcosm)	Infrastructure	Optical Micro Machines (OMM)	Optical
Cronos	Infrastructure	Transparent Optical	Optical
Integrated Sensing Systems	Infrastructure	Umachines	Optical
MEMSCAP	Infrastructure	Xros	Optical
PHS MEMS	Infrastructure	Crossbow	Sensornets
Standard MEMS	Infrastructure		
Tronics Microsystems	Infrastructure		

Table C.8
Select Mergers and Acquisition activity involving U.S. MEMS companies

Advanced MicroMachines	BFGoodrich
Xros	Nortel
Cronos	JDSU
Intellisense	Corning
Clinical Micro Sensors	Motorola
Silicon Light Machines	Cypress Semiconductor
BCO	Analog Devices
Kionix	Calient
Total Micro Products	Kymata

REFERENCES

[C1] Commercialization of Microsystems 2000, Santa Fe, NM, U.S., September, 2000.

[C2] J. Bryzek, Transducers '01 article.

[C3] B. Detlefs, "MEMS 1998: Emerging Applications and Markets," November 19, 1998.

[C4] http://www.delphiauto.com/news/pressReleases/pr1689-06042001, ca. September, 2001.

[C5] http://www.ultratech.com/products/mems_market.shtml, ca. September, 2001.

[C6] http://www.evgroup.com/products/waferbonding.htm, ca. September, 2001.

[C7] http://www.stsystems.com/, ca. September, 2001.

Table C.9
Academic MEMS Research Programs (Primarily U.S.)

Institution	Fabrication & mat'ls	rf MEMS	OptoMEMS	Mechanical devices	bio-MEMS/fluidics	Primary Strengths	Affiliations with MARCO, SRC, DARPA, etc.	Selected Web Sites
Some U.S. research programs								
Arizona State University		•		•		- rF MEMS (John Papapolymerou)		
CalTech	•	•	•	•	•	- Fabrication of optical, electronic, and magnetic devices (Axel Scherer) - Single-molecule biophysics (Stephen Quake) - Waveguide resonator coupling (Ammon Yariv) - Optical switching, waveguide-microresonator-to-waveguide, etc. (Yu-Chong Tai) - Ultralow power VHF/UHF (Roukes) - rF receivers, antennas, pathces, etc. (David Rutledge)	- DARPA funded	http://thebigone.caltech.edu/quake/ http://www.its.caltech.edu/%7Emmic/reshpubindex/reshpubindex.html
Case Western University	•			•		- Materials and fabrication of MEMS micromachines (motors, scanners, optics, etc. (Mehran Mehregany)	- DARPA funded	
CMU	•			•		- Integration of MEMS and CMOS process technologies (David Nagle) - Inertial MEMS, AFM array memory (Gary Fedder) - Jet cooling (Qiao Lin)	- DARPA and MARCO funded	http://www.ece.cmu.edu/research/projects/index.shtml#mems http://www.me.cmu.edu/faculty1/lin/lin.html http://www.c2s2.org
Cornell	•	•			•	- Large, shared fabrication facility, the "Cornell Nanofabrication Facility" - bio-MEMS: e.g., monolithic nanofluid sieving structures, biological logic (Craighead, Ewing, Scheraga)	- As a national facility, Cornell's fab is used by many researchers from around the U.S. - DARPA funded	http://www.nnf.cornell.edu/ http://www.cnf.cornell.edu/2000cnfra/2000cnfra.html
Georgia Institute of Technology				•	•	- Aircraft-related MEMS technology (Mark Allen) - microneedles for drug delivery	- DARPA funded	

Table C.9
Academic MEMS Research Programs (Primarily U.S.) (continued)

Institution	Fabrication & mat'ls	rf MEMS	OptoMEMS	Mechanical devices	bio-MEMS/fluidics	Primary Strengths	Affiliations with MARCO, SRC, DARPA, etc.	Selected Web Sites
Harvard	•				•	- New classes of materials (e.g., organic polymers) and new methods of fabrication (e.g., microprinting, micromolding) (George Whitesides) - Biological-to-electronic interface with pores of ATP synthase in silicon nitride barrier (Julie McGeoch)	- DARPA funded	
MIT	•	•	•	•		- Microsystems Technology Labs (Gray, Hagood, Kolodzieski, Reif, Schattenburg, Schmidt, Senturia, Smith, and many others) - Critical mass of PIs working on 50+ MEMS projects - Fabrication technology applied to sensors, actuators, and measurement of microelectronic materials (Steve Senturia) - Photonic Center (Kim Kimerling)	- MARCO funded - DARPA funded	
Northeastern University				•		- switches		http://www.ece.neu.edu/ edsnu/zavracky/mfl/ programs/ programs.html
Oak Ridge National Laboratory					•	- bio-MEMS from soup to nuts: cell lysis, dialysis, preconcentration, PCR, electrophoresis, detection, biomolecular optoelectronic devices, etc. - Biomolecular optoelectronic device via photovoltaics of photosystem I (Michael Simpson)	- Strong ties with Caliper - Long-standing DOE support	
Ohio State				•	•	- heat-sink cooling (Vafai) - Mauro Ferrari, bio-MEMS	- polymer microparticles for drug delivery (Derek Hansford)	
Pacific Northwest National Lab (Battelle)	•				•	- Capillary electrophoresis as ESI - front-end (Richard Smith) - 3-D microlaminates - Ceramic integration	- DARPA funded	
Penn State	•				•	- Nanomaterials (Steve Fonash)	- bio detectors, separations (Ewing)	

Table C.9
Academic MEMS Research Programs (Primarily U.S.) (continued)

Institution	Fabrication & mat'ls	rf MEMS	OptoMEMS	Mechanical devices	bio-MEMS/fluidics	Primary Strengths	Affiliations with MARCO, SRC, DARPA, etc.	Selected Web Sites
Sandia National Lab	•		•	•	•	- OptoMEMS, silicon photonics, bio-MEMS - Extensive development of manufacturing technologies, particularly LIGA and polysilicon surface micromachining - Encyclopedic staff and facilities, spanning design through test	- Heavy, sustained funding by U.S. Department of Energy - Close ties with U.C. Berkeley and University of New Mexico	
Stanford	•	•	•	•	•	- bio-MEMS (Tom Kenny, Ken Goodson, Greg Kovacs, Fabian Pease, David Blume, Olegard, Richard Zare, - Scanned probe arrays (Calvin Quate)	- DARPA funding - Most of the Stanford profs working in MEMS appear to be involved in a relatively high number of pre-existing business relationships	
U.C. Berkeley	•	•	•	•	•	- Berkeley Sensor & Actuator Center (Ex. Dir: John Huggins. Faculty Directors: Bernhard Boser , Roger Howe, Luke Lee, Dorian Liepmann, Liwei Lin, Richard Muller, Norman Tien (UCD),Albert Pisano, Kris Pister and Richard White) - Critical mass of PIs working on more than 100 MEMS projects covering a wide spectrum of topics - 30+ industrial sponsors - Large, shared fabrication facility	- Consistently large DARPA funding	http://www-bsac.eecs.berkeley.edu/
U.C. Davis		•	•	•		- Polysilicon surface micromachining (Norman Tien) - U.C.D. Microfabrication Facility, "the largest academic facility in the U.S. devoted to teaching and research"		http://www.ece.ucdavis.edu/ultra/WebPage/ http://www.ece.ucdavis.edu/ultra/WebPage/Microphotonics_research.htm
U.C.L.A.			•			- OptoMEMS (Chih-Ming Ho, Ming Wu) - SOI-based planar waveguide WDM technology (B. Jalali) - Chip-cooling (Chih-Ming Ho)	- A large amount of DARPA funding	

Table C.9
Academic MEMS Research Programs (Primarily U.S.) (continued)

Institution	Fabrication & mat'ls	rf MEMS	OptoMEMS	Mechanical devices	bio-MEMS/fluidics	Primary Strengths	Affiliations with MARCO, SRC, DARPA, etc.	Selected Web Sites
U.C.S.B.			•	•		- Outstanding VCSEL program - Center for Optoelectronics (Larry Coldren) - Center for Multidisciplinary Switch Technology (John Bowers)	- DARPA funding for aircraft-related MEMS - Lead university for DARPA funded Heterogeneous Optoelectronic Technology Ctr	
University of Colorado		•	•			- programmable antenna array (Y.C. Lee) - tuning elements for millimeter-wave - micromirror arrays	- DARPA funded	http://mems.colorado.edu/c1.gen.prjct/
University of Michigan	•	•	•	•	•	- Wireless Integrated Microsystems Consortium (WIMS) (Ken Wise, Khalil Najafi, Clark Nguyen, and many others) - Critical mass of PIs working on a large number of projects all focused on biosensors for chemical warfare - Heavy industrial support and involvement	- Consistently large DARPA funding	http://www.eecs.umich.edu/eecs/research/wims.html
University of New Mexico	•		•			- REPDs and VCSEL program (Julian Cheng) - Self-assembled nanostructures (Jeff Brinker, Gabriel Lopez) - Lead university for DARPA-funded Center for High Capacity Optoelectronic Interconnect (Director Steven Brueck)	- DARPA funded - Close ties with Sandia National Labs	
University of Texas at Austin		•	•			- OptoMEMS (Dean Neikirk - Center for the Design and Fabrication of Sensor Arrays, a Beckman Foundation Technologies Initiative)		

Table C.9
Academic MEMS Research Programs (Primarily U.S.) (continued)

Institution	Fabrication & mat'ls	rf MEMS	OptoMEMS	Mechanical devices	bio-MEMS/fluidics	Primary Strengths	Affiliations with MARCO, SRC, DARPA, etc.	Selected Web Sites
University of Washington	•				•	- Center for Applied Microtechnology - Fluidic self-assembly (Karl Bohringer) - On-chip immunoassays - Microfluidics for cultured neurons (Albert Folch)	- Strong ties to Micronics, a UW-assisted spin-off	http://www.ee.washington.edu/class/539/Lectures/lecture20/sld020.htm http://www.engr.washington.edu/~cam/ http://www.ee.washington.edu/faculty/darling/eefacrbd/projects.htm http://faculty.washington.edu/yagerp/pyresearch.html
U.S.C.	•	•	•	•		- Piezoelectric film-deposition for rF resonators (Eun Sok Kim) - VCSEL and small VCSEL (D. Dapkus) - Acoustic-wave liquid ejector & mixers; hydrophones (Kim)	- Multiple DARPA-supported OI centers	http://mems.usc.edu/
Some international research programs								
University of Twente	•	•	•	•	•	- Critical mass of 20+ PIs (Albert Van den Berg)	- MESA Research Institute	- Microdialysis membranes and silicon sensors (P. Bergveld)
Technion Israel Institute of Technology			•	•	•	- Ion sensitive FETs, FIR sensors, actuators (Yael Nemirovsky)	- Opto/CMOS integration (Josef Salzman)	- Self-controlled drug delivery system, logic gates (Noah Lotan)
Institut fur Mikrotechnik Mainz	•		•		•	- OptoMEMS - Materials - LIGA fabrication	- German government funded	http://www.imm-mainz.de/content.html
IMEC	•		•			- Fiber bundle based CMOS chip-to-chip short distance optolink (Christiaan Baert)	- Intel has excellent relations with IMEC	
Fraunhofer Institute Wuerzburg	•		•			- Organo-ceramic materials for packaging waveguides, gratings, prisms and VCSEL focusing lenses	- ESPRIT	
Fraunhofer Institute IZM	•		•			- Thermoplastic embossing of waveguides on package		
Imperial College	•				•	- On-chip bioseparations (Andreas Manz, Oliver Hofmann)		http://155.198.226.63/manz/

Table C.9
Academic MEMS Research Programs (Primarily U.S.) (continued)

Institution	Fabrication & mat'ls	rf MEMS	OptoMEMS	Mechanical devices	bio-MEMS/fluidics	Primary Strengths	Affiliations with MARCO, SRC, DARPA, etc.	Selected Web Sites
University of Alberta					•	- bio-MEMS (Jed Harrison)	- Close ties to start-ups, esp. Alberta Microelec	
ETH Zurich	•			•		- Sensors and actuators	- Fabrication methodology	http://www.iqe.ethz.ch/pel/Welcome.html http://www.ifm.mavt.ethz.ch/mems/projects.htm
University of Dortmund			•		•	- OptoMEMS - bio-MEMS		http://www-hft.e-technik.uni-dortmund.de/uk/forschng/forschng.html
Fraunhofer Institute Jena			•			- VCSELs and detectors	- Si V-groove sub-assemblies - Fiber-VCSEL alignment	

APPENDIX D. GLOSSARY

AFMs	atomic force microscopes
AIST	National Institute of Advanced Industrial Science and Technology
ASIC	application specific integrated circuit
ADXL	Families of precision dual axis accelerometers on a single chip produced by Analog Devices, Inc.
B-MLA	backlight-micro lens arrays
BSAC	Berkeley Sensor & Actuator Center of the University of California at Berkeley
CCD camera	charge coupled device camera
CIRMM	Center for International Research on Micromechatronics at the University of Tokyo
CMOS	complementary metal oxide semiconductor
CNRS in France	Centre National de la Recherche Scientifique
CRDL	Toyota Central R&D Laboratories
DARPA	U.S. Defense Advanced Research Projects Agency
DRIE	Deep-reactive-ion-etching
EMI suppression	electro-magnetic interference
EMR	electro-mechanical relays
ENOSE	electronic nose
FCVA	Filtered Cathodic (i.e., carbon) Vacuum Arc Deposition, a kind of thin-film coating discussed at Sony
FET	field effect transistor
FIB	focused ion beam etching and deposition
GFLOPS	giga floating point operations per second
GMs	genetic modifications
HDI	General Electric’s High Density Interconnect process
ICP	inductively coupled plasma
IMT	Institute of Microchemical Technology founded by Prof. Kitamori
ISEMI (a METI lab)	a research group Institute of Mechanical Systems Engineering. The research group is called ISEMI, an acronym that honors the late Dr. Isemi Igarashi, the founder of silicon MEMS in Japan.
KAST	Kanagawa Academy of Science and Technology

LBNL	UC Berkeley/LBNL
LIGA	a German acronym that stands for Lithographic Galvonoformung Abformung, (or lithography, electroplating, molding); see http://www.memsguide.com/MEMSequipments-Micromachining_LIGA.htm
MCNC-Cronos-JDS	created the SMARTMUMPS process; Cronos Integrated Microsystems (formerly MCNC MEMS Technology Center
MEMS	microelectromechanical systems or microsystems, defined as the use of microfabrication techniques to create mechanical structures in silicon and other materials
MERL	Hitachi's Mechanical Engineering Research Laboratory
METI	Ministry of Economy, Trade and Industry
MicroTAS	micro total analysis systems
MICS	Multi-user Integration Chip Service, a foundry system at Ritsumeikan University
MITI	Ministry of International Trade and Industry
MMC TR	Micromachine Center (MMC) Technical Report (TR)
MOEMS	Micro-Opto-Electro-Mechanical Systems
MOS	Multi Organoleptic Systems
MPT	Micromachine Technology Project
MTO	DARPA Microsystems Technology Office
MUMPS	Multi-User MEMS Processes
NDA	non disclosure agreement
NEDO	New Energy and Technology Development Organization of Japan
NERs	Nanoscale Exploratory Research program of NSF
NEXUS	A non profit association for microsystems professionals, which is headquartered in Grenoble
NICHE	New Industry Creation Hatchery Center at Tohoku University
NIRT	Nanoscale Interdisciplinary Research Teams, teams of 3-5 people from various disciplines to work together for 3-5 years on an interdisciplinary nanotechnology project
NIST	U.S. National Institute of Standards and Technology
NMASP	Nano-Mechanical Array Signal Processors
NNI	National Nanotechnology Initiative
NNUN	National Nanofabrication Users Network operated by the U.S. National Nanofabrication Facility

NNUF	U.S. National Nanofabrication Facility
ONR	U.S. Office of Naval Research
PCR	polymerase chain reaction
PDMS	poly-dimethylsiloxane
P-MLA	projector-micro lens arrays
PMMA	poly–methylmetacrylate
RF MEMS	radio frequency MEMS
RIMST	the Research Institute for Microsystems Technology at Ritsumeikan University
SAW device	surface acoustic wave devices
SPS	a group or division of Motorola
SSR	solid-state relays
SUMMIT	Sandia National Laboratories
TEM	transmission electron microscope
TLM	thermal lens microscope
TLOs	technology licensing offices
UARC	University Affiliated Research Center to support nanofabrication sponsored by the Center of Research for Nanoscience for the Soldier, a subsidiary of the U.S. Army Research Office
VBL	Venture Business Laboratory at Tohoku University
VDEC	VLSI Design and Education Center at the University of Tokyo
WIMS	Wireless Integrated Microsystems Center, an NSF Engineering Research Center at the University of Michigan